

U.S. Mines, Bureau of
Bulletin 135

DEPARTMENT OF THE INTERIOR

FRANKLIN K. LANE, SECRETARY

BUREAU OF MINES

VAN. H. MANNING, DIRECTOR

COMBUSTION OF COAL AND
DESIGN OF FURNACES

*TN
23
44
no. 135*
BY

HENRY KREISINGER, C. E. AUGUSTINE

AND

F. K. OVITZ

ENGINEERING

ENGINE STORAGE



WASHINGTON
GOVERNMENT PRINTING OFFICE

1917

Bulletin 135

DEPARTMENT OF THE INTERIOR

FRANKLIN K. LANE, SECRETARY

BUREAU OF MINES

VAN. H. MANNING, DIRECTOR

COMBUSTION OF COAL AND DESIGN OF FURNACES

BY

HENRY KREISINGER, C. E. AUGUSTINE

AND

F. K. OVITZ



WASHINGTON
GOVERNMENT PRINTING OFFICE
1917

The Bureau of Mines, in carrying out one of the provisions of its organic act—to disseminate information concerning investigations made—prints a limited free edition of each of its publications.

When this edition is exhausted, copies may be obtained at cost price only through the Superintendent of Documents, Government Printing Office, Washington, D. C.

The Superintendent of Documents is *not an official of the Bureau of Mines*. His is an entirely separate office, and he should be addressed:

SUPERINTENDENT OF DOCUMENTS,
Government Printing Office,
Washington, D. C.

The general law under which publications are distributed prohibits the giving of more than one copy of a publication to one person. The price of this publication is 20 cents.

First edition. October, 1917.

CONTENTS.

	Page.
Introduction.....	1
Personnel.....	2
Purpose and scope of combustion investigations.....	2
Reasons for selecting a special furnace.....	4
Scope of this report.....	5
Practical deductions from investigations.....	6
General summary.....	6
Relation of completeness of combustion to size of combustion space.....	7
Rate of feeding air and coal.....	7
Character of fuel.....	7
Stratification of gases.....	8
Content of CO ₂ and CO in gases.....	8
Effect of gas samplers on temperature drop.....	9
Burning of volatile matter.....	9
Combustion tests.....	10
General statement.....	10
Description of apparatus.....	10
Method of conducting experiments.....	12
Method of starting and stopping the tests.....	14
Conditions during the tests.....	14
Weight of ash and refuse.....	14
Sampling and analyzing furnace gases.....	15
Gas-sampling tubes.....	16
Gas-collecting apparatus.....	17
Apparatus for collecting samples of soot and tar.....	20
Analysis of gas samples.....	21
Determination of tar and soot.....	21
Temperature measurements.....	22
Gas-pressure measurements.....	23
Coals used in the tests.....	23
Method of sampling.....	24
Results of the experiments.....	25
Variation of conditions during tests.....	25
Tabulated results.....	25
Discussion of combustion process in combustion space.....	54
Undeveloped heat of furnace gases along their path of travel.....	61
Effect of the percentage of excess air and the rate of firing on completeness of combustion.....	68
Size of combustion space required for any desired completeness of combustion, rate of firing, and excess of air.....	68
Practical application of results.....	76
Effect of length of gas travel on the completeness of combustion.....	77
Effect of composition of coal on the size of combustion space required.....	78
The effect of the quantity of the volatile matter.....	78
The effect of the quality of the volatile matter.....	81

Discussion of combustion process in combustion space—Continued.

Effect of composition of coal on the size of combustion space required—Continued.	Page.
Oxygen as an indicator of the burning quality of coals.....	83
The effect of moisture in coal on combustion.....	86
Relation between kind of coal used and the completeness of combustion.....	88
Determination of the size of the combustion space of a furnace to burn a given coal.....	88
The most economical air supply for a given furnace and given fuel....	90
Discussion of miscellaneous data.....	97
Stratification of gases.....	97
Accuracy of average composition of gas samples.....	104
Relation between proportion of CO ₂ in the furnace gases and the excess of air.....	105
Relation between the percentage of CO and the total combustible gases....	105
Relation between CO content in gases and amount of undeveloped heat...	108
Temperature drop along the path of gases in the long combustion chamber.	109
Heat absorbed by water in gas samplers.....	109
Radiation losses from walls and roof of furnace.....	110
Heat radiated to opening under boiler.....	110
Temperature of flames at section A higher than average temperature of gases at the same section.....	111
Discussion of the process of combustion above the fuel bed.....	112
Smoke is formed at or near surface of the fuel bed.....	116
Causes of the slow burning of soot in a furnace.....	117
Reason for success of mechanical stokers in burning soft coal without smoke.	118
Distillation of volatile matter at low temperature.....	118
Distillation of the volatile matter in presence of oxygen.....	119
Stability of hydrocarbons.....	123
Physical chemistry of combustion over the fuel bed.....	125
Concentration or mass action.....	125
Mixing of air and gases.....	129
Temperature in combustion chamber.....	132
Time of contact.....	133
Future methods of using bituminous coal.....	134
The advantages of liquid fuel.....	136
Conclusion.....	137
Publications on the utilization of coal and lignite.....	138

 TABLES.

TABLE 1. Analysis of coals used in the tests.....	24
2. Sizes of coal as burned.....	24
3. Results of combustion tests.....	30
4. Chemical characteristics of the three coals tested.....	78
5. Size of combustion space required for the three coals when burned under conditions given in columns 1, 2, and 3.....	79
6. Relation between the kind of coal and the completeness of combustion when other conditions are constant.....	88


	Page.
TABLE 7. Composition of three given coals and factors indicating their burning qualities.....	89
8. Results of analysis of individual gas samples collected in test 188, with Pittsburgh screenings.....	98
9. Results of analysis of individual gas samples collected in test 195, with Pittsburgh screenings.....	99
10. Results showing percentages of excess air calculated for individual simultaneous gas samples, showing stratification of gases.....	102
11. Results showing weights of combustible gases, tar, and soot arising from fuel bed, in grams per cubic foot of gas at 60° F. and 30 inches pressure.....	112

ILLUSTRATIONS.

PLATE I. Experimental furnace.....	10
FIGURE 1. Process of combustion of coal in a hand-fired furnace.....	3
2. Horizontal and vertical longitudinal sections through experimental furnace.....	11
3. Sections through the stoker, showing construction of the arch and method of supplying air to the tuyères.....	13
4. Plan view showing position of gas and tar samplers at surface of the fuel bed and 11 inches above it.....	15
5. Position of tar and gas samplers at section A of combustion furnace..	16
6. Position of gas samplers at sections beyond section A of combustion furnace.....	16
7. Position of tar and gas samplers over the fuel bed.....	17
8. Water-cooled gas sampler having three gas-sampling tubes in one water jacket.....	18
9. Diagram of apparatus used in sampling gases, tar, and soot.....	19
10. Comparison of temperatures in combustion chamber at section G, as measured with Hoskins thermocouple and Wanner pyrometer...	22
11. Variation of conditions and period of sampling in test 179.....	26
12. Variations of conditions and period of sampling in test 173.....	27
13. Progress of composition of furnace gases at various distances above the fuel bed.....	54
14. Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 20, 30, and 40 pounds.....	56
15. Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 50 and 60 pounds.....	57
16. Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pocahontas coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	58

	Page.
TABLE 17. Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	59
18. Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Illinois coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	60
19. Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 20, 30, and 40 pounds.....	63
20. Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 50 and 60 pounds.....	64
21. Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pocahontas run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	65
22. Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	66
23. Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Illinois run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.....	67
24. Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pittsburgh screenings.....	69
25. Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pocahontas coal.....	70
26. Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pittsburgh run-of-mine coal.....	71
27. Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Illinois coal.....	72
28. Completeness of combustion along the path of the gases with four percentages of excess of air and average rates of combustion of 25 and 50 pounds, as shown by tests made with Pittsburgh run-of-mine coal.....	73
29. Results of tests with Illinois and Pocahontas coal showing relation between the required size of combustion space, a given completeness of combustion, the rate of firing, and the percentage of excess air.....	74
30. Results of tests with Pittsburgh run-of-mine and Pittsburgh screenings showing relation between the required size of combustion space, a given completeness of combustion, the rate of firing, and the percentage of excess air.....	75

FIGURE 31. Relation between volatile matter of coal and size of combustion space required.	80
32. Relation between size of combustion space required and the chemical properties of three coals.	82
33. General characteristics of various fuels and their relation as shown by their carbon, hydrogen, and oxygen contents reduced to moisture-free, ash-free, nitrogen-free, and sulphur-free basis, plotted on trilinear coordinates.	85
34. Relation between the percentage of water vapor and the velocity of reaction between two volumes of CO and one volume of O ₂	86
35. Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Pocahontas coal.	91
36. Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Pittsburgh coal. .	92
37. Effect of air supply on the two principal sources of heat loss in a steam generating apparatus as shown by tests of Illinois coal; rate of firing, 50 pounds.	93
38. Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Illinois coal, rate of firing, 25 pounds.	94
39. Curves showing percentage of excess air giving the minimum heat losses in burning Pittsburgh, Pocahontas, or Illinois coal in various sizes of combustion space.	95
40. Relation between the percentage of CO ₂ in the gases and the percentage of excess of air used in combustion.	106
41. Relation between percentages of CO and H ₂ , CH ₄ , and the total gaseous combustible in furnace gases.	107
42. Relation between CO content in furnace gases and heat loss due to the escape of all unburned gases.	108
43. Diagram showing temperature drop from radiation.	111
44. Weight of soot and tar in furnace gases at the surface of, 1 foot from, and an average of 5 feet from the fuel bed.	114
45. Principal methods of feeding coal and air in commercial furnaces. .	120



Digitized by the Internet Archive
in 2011 with funding from
University of Toronto

COMBUSTION OF COAL AND DESIGN OF FURNACES.

By HENRY KREISINGER, C. E. AUGUSTINE, and F. K. OVITZ.

INTRODUCTION.

The Bureau of Mines is conducting investigations to determine how fuels belonging to or for the use of the United States Government can be utilized with greater efficiency. As a result of these investigations a number of reports have been published, each report treating of one phase of fuel utilization. A list of these publications is given at the end of this bulletin.

The efficient utilization of coal depends on the correct design of furnaces and on their proper operation. To attain both of these conditions a knowledge of the fundamental principles of combustion is necessary. Therefore, the study of the combustion of coal in industrial furnaces has been made a part of the bureau's fuel investigations.

The desirability of investigating the fundamental principles of combustion was suggested by the study of a large number of steaming tests made by the fuel-testing division on coals from all of the more important fields in the United States. The results of these tests have been published in Bulletin 325^a of the United States Geological Survey and in Bulletin 23^b of the Bureau of Mines.

As a result of that study a plan to investigate the combustion of coal in a special apparatus in which all conditions could be controlled was presented to the National Advisory Board for Fuels and Structural Materials at its meeting of April 10 and 11, 1906. The plan received the approval of the board, and since the establishment of the experiment station of the Bureau of Mines at Pittsburgh the investigation of the combustion of coal has been carried on intermittently. The history of these investigations is given in Technical Paper 63.^c

^a Breckenridge, L. P., A study of four hundred steaming tests made at the fuel-testing plant, St. Louis, Mo., in 1904, 1905, and 1906: U. S. Geol. Survey Bull. 325, 1907, 196 pp.

^b Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coal and related investigations, Sept. 1, 1904, to Dec. 31, 1908: Bull. 23, Bureau of Mines, 1912, 380 pp.

^c Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces: Tech. Paper 63, Bureau of Mines, 1914, 46 pp.

PERSONNEL.

The combustion investigations reported in this bulletin were conducted by one fireman and five observers, three of whom were chemists collecting and analyzing samples of gases. The following men were at various times members of the crew: W. T. Ray, H. Kreisinger, J. K. Clement, J. C. W. Frazer, E. J. Hoffman, C. E. Augustine, F. K. Ovitz, A. E. Hall, L. L. Satler, A. L. Smith, V. B. Bonny, E. T. Gregg, L. H. Adams, W. L. Egy, and J. P. Stein.

Chemical analyses of coal and refuse were made under the direction of A. C. Fieldner, chemist, of the Bureau of Mines.

PURPOSE AND SCOPE OF COMBUSTION INVESTIGATIONS.

In practically all industrial furnaces the combustion of coal takes place in two stages—(1) combustion in the fuel bed, which includes the distillation of volatile matter and partial combustion or gasification of the fixed carbon; and (2) combustion of the gaseous and other combustible rising from the fuel bed in the combustion space.

The processes of combustion in a hand-fired furnace can be best explained by reference to figure 1. In the figure the curves show the percentages of the different gases at various points in the fuel bed and in the combustion space. The changes in the percentage of each gas indicate the process of combustion. The fuel bed is shown to be 6 inches thick. The oxygen (O_2) is all used at about $3\frac{1}{2}$ inches from the grate. At the same point the carbon dioxide (CO_2) reaches a maximum of about 12 per cent. Beyond this point the percentage of CO_2 drops and the percentage of carbon monoxide (CO) and other combustible increases rapidly, showing that the CO_2 is reduced by contact with hot carbon to CO. At the surface of the fuel bed the gases contain about 26 per cent of combustible, no oxygen, and about 8 per cent of CO_2 . Air is added over the fuel bed and the combustible is burned in the combustion space. At the end of 7 feet of the combustion space, the combustible gases are burned to 4 per cent and at the same time the CO_2 increases to 14 per cent. With a combustion space long enough the percentage of combustible would be reduced practically to zero.

The three main processes in the fuel bed are the oxidization of carbon to CO_2 , the reduction of CO_2 to CO, and the distillation of volatile matter. The zones where these three processes take place are indicated at the top of figure 1, and are called the oxidizing zone, the reducing zone, and the distillation zone. The boundaries between the three zones are not distinct, the zones merging gradually into one another.

The combustion investigations of the bureau are carried on in two parts. One part is the study of the processes of combustion in the fuel bed as affected by the rate of supplying air through the fuel bed, by

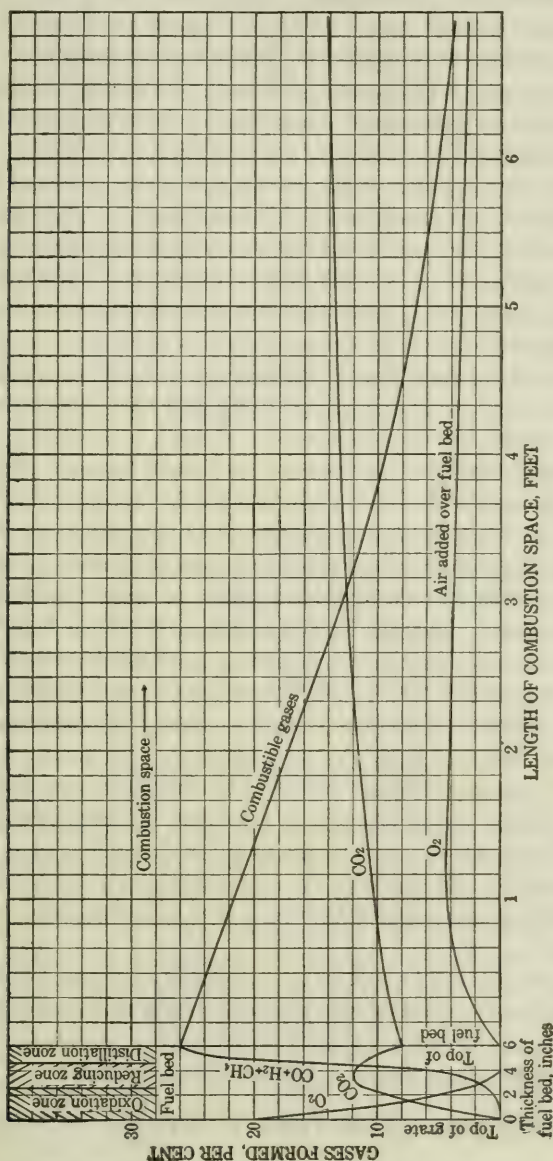


FIGURE 1.—Process of combustion of coal in a hand-fired furnace.

the character of the fuel as regards structure and composition, by the thickness of fuel bed, by the method of feeding the coal and the air, and by the method of heating the coal. Investigations so far completed show that the fuel bed in most industrial furnaces acts pri-

marily as a gas producer. The gases rising from a level fuel bed contain 15 to 32 per cent of combustible gases, about 8 per cent of carbon dioxide, and practically no free oxygen. This is true of even 6-inch fuel beds and rates of combustion as high as 120 pounds of coal per hour per square foot of grate. The process of combustion in the fuel bed is treated more thoroughly in Technical Paper 137.^a

The second part of the investigation is the study of the process of combustion of the gases and other combustible rising from the fuel bed in the combustion space, after a sufficient quantity of air has been added. The results of the study are given in this report.

The process of combustion in the combustion space is influenced by many factors, the most important of which are the following: The volume and shape of the combustion space; the kind of coal used, especially the character, and the amount of the volatile matter it contains; the rate of firing; the quantity of air supplied over the fuel bed; the rate of mixing the air with the combustible rising from the fuel bed; the rate of heating the coal; and the temperature in the combustion space.

The qualitative effects on the rate and completeness of combustion of many of these factors have been known for a long time. Thus, for example, it has been generally known that the higher the percentage of volatile matter in the coal and the higher the rate of combustion, the larger must be the combustion space to attain practically complete combustion. But the exact relation of these factors was not known; that is, the quantitative data presented in some convenient units, such as pounds, feet, or percentages, were lacking. It was to obtain such definite relations that the study of combustion in the space beyond the fuel bed was undertaken. On pages 68 to 89 are given data for proportioning the combustion spaces of industrial furnaces; these data, being the result of direct experimental work, furnish a more rational basis for design than has heretofore been available.

The apparatus so far used in the investigation was a special furnace having a combustion space 3 feet by 3 feet in cross section and about 40 feet long.

Provision was made to collect gas samples at about 5-foot intervals along the path of travel of the gases through the combustion space. Analyses of these samples furnished the principal data for the study of the process of combustion in the combustion space.

REASONS FOR SELECTING A SPECIAL FURNACE.

So many factors influence the process of combustion that it is impossible to get concordant results if all the factors vary at once. The apparatus and the experiments must be so planned that only

^a Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., *Combustion in the fuel bed of hand-fired furnaces*: Tech. Paper 137, Bureau of Mines, 1916, 76 pp.

one factor is varied at a time, while the other factors are fixed or made constant. The design of the apparatus must be such that a complete set of accurate observations can be taken. It was mainly for these reasons that the special furnace was chosen.

The first steps in the investigation were to study the effects of the size of the combustion space, of the rate of combustion, of the kind of coal, and of the air supply. The rate of heating, and the rate of mixing air added over the fuel bed with combustible gases were to be kept as constant as practicable. Only the normal mixing in the stoker and the natural diffusion of gases entered into the series of tests so far conducted. One reason for starting the investigation with this limited mixing was that most industrial furnaces operate under similar conditions. Another reason was to obtain time and experience for devising effective means for mixing and some convenient way of expressing the speed and thoroughness of mixing. It was realized at the time of planning these investigations that the rate of mixing of air added over the fuel bed with the combustible rising from the fuel bed greatly affects the rapidity of the combustion of the gases. The importance of mixing has been pointed out by Breckinridge.^a

Since the investigations recorded in this report were made the experimental furnace has been so modified that any quantity of air can be introduced over the fuel bed with controllable velocities and in four different directions, producing different rates of mixing. A series of tests has been started with this modified furnace with the object of determining the effect of mixing on the rapidity of combustion of the volatile matter of coal in the combustion space.

SCOPE OF THIS REPORT.

This report treats of the processes of combustion of the combustible substances rising from the fuel bed, which must be burned in the combustion space of the furnace. In other words, it considers the processes taking place in the furnace between the top of the fuel bed and the place where the gases leave the furnace. The knowledge of these processes makes it possible to determine the proper design of the combustion space of a furnace for burning a given coal under a given set of conditions.

This bulletin is a companion report to Technical Paper 137,^b and is a more complete report of the investigations, a part of which were reported in Technical Paper 63.^c

^a Breckenridge, L. P., A study of four hundred steaming tests made at the fuel-testing plant, St. Louis, Mo., in 1904, 1905, and 1906: U. S. Geol. Survey Bull. 325, 1907, p. 178.

^b Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces: Tech. Paper 137, Bureau of Mines, 1916, 76 pp.

^c Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces: Tech. Paper 63, Bureau of Mines, 1914, 46 pp.

The material presented consists mainly of the description of about 100 tests made in the special furnace having a long combustion space; the tabulated and plotted results of these tests; and the discussion of these results with deductions furnishing the basis for rational furnace design. The tests were made with three kinds of coal, namely, Pocahontas, Pittsburgh, and Illinois coal. The coals were burned at five rates—20, 30, 40, 50, and 60 pounds per square foot of grate per hour. Several tests were made with each coal at each rate of combustion, each test being run with a different percentage of excess air.

The material is arranged in four parts. The first part contains the description of the apparatus and the methods of conducting the experiments; the second part gives the results of the experiments, explains their meaning and points out their practical application; the third part consist of discussions of miscellaneous observations; and the fourth part contains a discussion of the process of combustion in the combustion space and of the laws that govern it.

PRACTICAL DEDUCTIONS FROM INVESTIGATIONS.

The practical deductions are given in figures 29, 30, 32, and 33 and the text on pages 68 to 89. The data shown in the figures may be used for proportioning the combustion space in designing furnaces. Although these data were obtained from experiments with a Murphy furnace and are therefore particularly applicable to furnaces of that type, it is believed that they may be a valuable guide in the proportioning of other furnaces. When applying the data to other furnaces the designer should give full consideration to the method of introducing secondary air and the facilities for mixing it with the combustible rising from the fuel bed. If the methods of introducing the air and the facilities for mixing it are better than those used in the experimental furnace, smaller combustion space than is indicated in the figures may be used. If, however, the methods are not as good the size of the combustion space should be increased. For the best results the secondary air should be introduced as near to the fuel bed as practicable, and the air should be supplied in a large number of streams at high velocities.

GENERAL SUMMARY.

The gases rising from the fuel bed of a Murphy stoker contain 10 to 28 per cent by volume of combustible. As the gases flow through the combustion space they mix with the air added over the fuel bed and burn. Because of this combustion the percentage of combustible decreases along the path of gases, the rate of decrease being rapid at first, but slowing down as the gases move farther from the fuel bed.

This combustion process is discussed on pages 54 to 61 in connection with figures 14 to 18, inclusive.

Inasmuch as the gases rising from the fuel bed contain 10 to 28 per cent of combustible and practically no free oxygen, additional air must be supplied over the fuel bed to insure complete combustion. In order that this additional air may flow into the furnace, the pressure of gases in the furnace must be somewhat below that of the outside air; in other words, there must be a "draft" over the fire. If the pressure in the furnace is nearly the same as that of the outside atmosphere, the additional air must be supplied under pressure with a blower or some other device. Therefore, a furnace can not be operated successfully with the so-called balanced draft, without supplying under pressure the necessary air over the fuel bed.

RELATION OF COMPLETENESS OF COMBUSTION TO SIZE OF COMBUSTION SPACE.

The combustible gases leaving the fuel bed represent 40 to 60 per cent of the total heat units in the coal, so that it can be said that, on an average, one-half of the combustion of coal takes place in the fuel bed and one-half in the combustion space. The completeness of combustion of the gases depends on the size of the combustion space. This feature of the combustion process is discussed in detail on pages 61 to 67 in connection with figures 19 to 23, inclusive.

RATE OF FEEDING AIR AND COAL.

The completeness of combustion with any given size of combustion space depends on the excess of air and the rate of firing the coal. In general, the smaller the excess of air and the higher the rate of firing the less completely are the furnace gases burned. The effect of these two factors on the completeness of combustion is discussed on page 68 in connection with figures 24 to 28, inclusive.

The application to furnace design of the relation between the completeness of combustion on the one hand and the size of combustion space, the excess of air and the rate of firing on the other, is given in pages 68 to 78 in connection with figures 29 and 30.

CHARACTER OF FUEL.

The effect of the composition of the coal on the required combustion space, when the coal is burned under a given set of conditions is discussed on pages 78 to 90 in connection with figures 31 and 32. In general, it can be said that for any given set of conditions as to rate of combustion and excess of air the required size of combustion space is approximately in direct proportion to the product of the percentage of the volatile matter times a factor representing its

quality. The indicator of the quality of the volatile matter is the ratio of the volatile carbon to available hydrogen. The more carbon in the volatile matter the more difficult the latter is to burn.

The size of the combustion space required for any set of conditions of combustion also appears to be directly proportional to the percentage of oxygen in the moisture-free and ash-free coal. However, it is very likely that the burning properties of the coal are not directly affected by the oxygen in the coal, but that the oxygen indicates the stage in carbonization of the original plant substance, and that this stage of carbonization, or the age of the coal, has a direct effect on burning properties.

The percentage of excess air that gives the best results in any steam-generating apparatus varies with the size of the furnace and the kind of fuel. In two furnaces burning the same fuel but having different sizes of combustion space, the one with the smaller combustion space will require more excess air for the best results than will the one with the larger combustion space. Also of two furnaces exactly alike in size, but burning different coals, the one burning the coal lower in volatile matter and oxygen gives the best results with lower excess of air than is necessary for the best results in the furnace burning the coal higher in volatile matter and oxygen. This fact explains why in one plant the highest efficiency may be obtained with 14 per cent of CO_2 in the gases and in another plant with only 10 per cent of CO_2 . This feature is discussed in detail on pages 90 to 97 in connection with figures 35 to 39, inclusive.

STRATIFICATION OF GASES.

The gases in the furnace are not of uniform composition; they tend to flow through the combustion space in stratified streams. This tendency to stratification retards combustion and makes gas sampling difficult, and persists even with the apparently violent mixing of the Murphy furnace. It is impossible to draw definite conclusions of the progress of combustion by taking only one gas sample at any one cross section of the combustion space. Even by taking several simultaneous samples at different points in any one cross section it is difficult to arrive at the average composition of the gases. This statement is true in varying degrees of all commercial furnaces. This feature is discussed on pages 97 to 104, inclusive.

CONTENT OF CO_2 AND CO IN GASES.

There is a definite relation for each coal between the excess of air supply and the percentage of CO_2 in the furnace gases. This relation is shown for Pocahontas, Pittsburgh, and Illinois coal in figure 40, and is discussed on page 105.

The total combustible gases at any cross section of the combustion space are proportional to the percentage of CO in the furnace gases. Approximately the percentage of CO forms four-fifths of the total combustible gases. The other one-fifth consists mainly of hydrogen; only a trace of methane is usually found in the gases. Therefore, by determining the percentage of CO in the furnace gases, the heat losses due to the escape of all combustible gases can be closely computed. The relation between the percentage of CO and these heat losses is shown in figures 41 and 42, and is discussed on pages 105 to 109.

EFFECT OF GAS SAMPLERS ON TEMPERATURE DROP.

The drop in temperature along the path of the furnace gases in the experimental furnace was mainly due to the heat absorption by the water-cooled gas samplers. The gas samplers were absorbing heat at the rate of one boiler horsepower on less than 0.25 square foot of exposed surface. This drop in temperature is discussed on pages 109 to 111.

BURNING OF VOLATILE MATTER.

The volatile matter leaves the fuel bed as complex hydrocarbon compounds. In the absence of sufficient oxygen for their complete combustion these hydrocarbons are quickly decomposed by the high furnace temperature into soot, hydrogen, and carbon monoxide. The formation of CO is due to the presence of CO₂ and the small supply of oxygen. At a distance of 1 or 2 feet from the surface of the fuel bed only a very small amount of hydrocarbons can be found in any state, gaseous, liquid, or solid. The solid substance present in the flames is mostly soot, with a trace of tars. This fact is shown in Table 11 and figure 44. All hydrocarbons are unstable at furnace temperature, and unless enough air to insure complete combustion is quickly mixed with them at the time they are distilled, they are quickly decomposed, the ultimate product consisting mostly of soot, H₂ and CO. Methane (CH₄), which is perhaps the most stable hydrocarbon, is found only in traces, 1 foot beyond the surface of the fuel bed. The persistence of CO in the furnace gases is not due to the difficulty of burning it, but to its constant formation by the reaction between soot and H₂ with CO₂. This is the reason why CO is found in the furnace gases after all other forms of combustible have practically disappeared. Under ordinary furnace conditions there is no need of analyzing for any other combustible gas when the CO content is less than 1 per cent.

Soot is formed at the surface of the fuel bed by heating the hydrocarbons in absence of air; it is not formed by the hydrocarbon gases striking the cooling surfaces of the boiler. As a matter of fact only a very small trace of the hydrocarbon gases ever reaches the surfaces of

the boiler; hydrocarbons that do so are prevented from decomposition by the cooling effect of the contact. The cooling surfaces do not cause the formation of soot, they merely collect soot and prevent its combustion. Hydrocarbons are stable at low temperatures but decompose readily at high temperatures.

Only when the furnace temperature is very low, say below 1,000° F., is there found an appreciable quantity of hydrocarbons 2 feet from the fuel bed. This subject is discussed in detail on pages 112 to 125.

The rapidity of burning combustible in the combustion space depends on the quantity of oxygen intimately mixed with the combustible. The larger this quantity the faster the combustible burns. This phase of the combustion process is considered on pages 125 to 129.

Thorough mixing of the gases produces a uniform mixture of the oxygen and the combustible, thereby making possible the most rapid combustion with any given air supply. In a large number of instances the rapidity of combustion is limited by the rate of mixing. Thus mixing is a very important factor in the attainment of good combustion. Mixing is discussed in more detail on pages 129 to 132.

COMBUSTION TESTS.

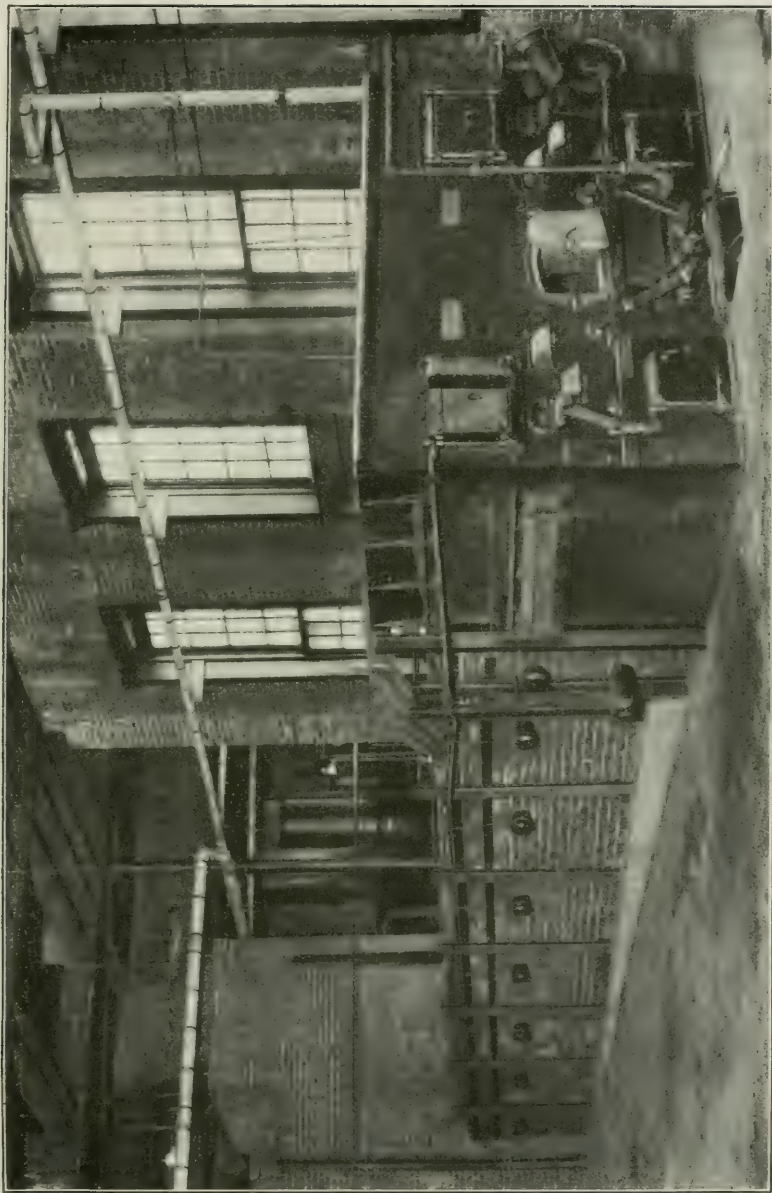
GENERAL STATEMENT.

The investigation of the combustion in the space of a furnace above the fuel bed was carried on in the special furnace having a horizontal combustion chamber about 40 feet long and of nearly constant cross section. The furnace was fed with a Murphy stoker, and the products of combustion were discharged from the end of the combustion chamber under a Heine boiler. Air was supplied under the grate and over the fuel bed with a fan blower. An exhaust fan provided sufficient reduction of pressure at the discharge end of the furnace.

The data obtained in these experiments are based mainly on series of experiments in which several sets of gas samples were simultaneously collected from the combustion space at intervals of about 5 feet along the path of the gases. Furnace temperatures were also measured at the places where the gas samples were collected. Gas pressures under the grate, over the fuel bed, and at the discharge end of the furnace were determined periodically. The coal was weighed as it was supplied to the furnace.

DESCRIPTION OF APPARATUS.

The general external appearance of the experimental furnace and its connection to the Heine boiler are shown in Plate I. A horizontal and a vertical longitudinal section through the furnace are shown in figure 2. The furnace is essentially a brick tunnel 3 by 3 feet



EXPERIMENTAL FURNACE. CONNECTIONS TO HEINE BOILER SHOWN.

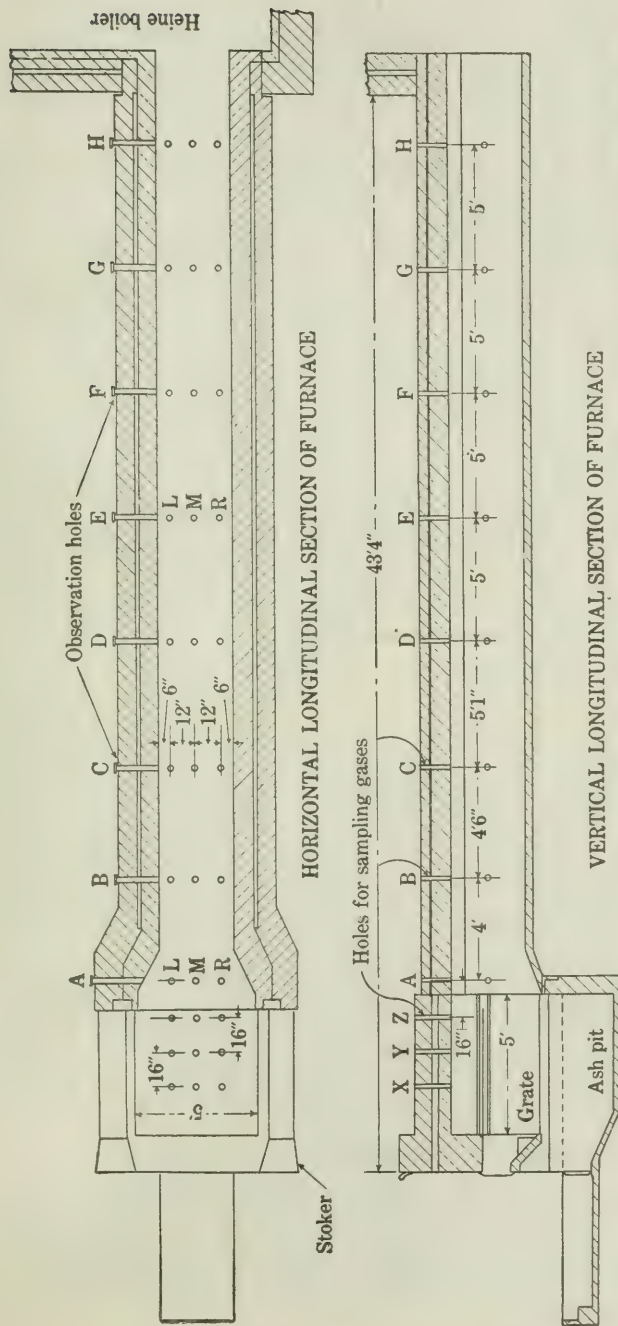


FIGURE 2.—Horizontal and vertical longitudinal sections through experimental furnace. A to H are sections where gas samples were taken. Circles show position of sampling holes. L, M, and R indicate left, middle, and right sampler, respectively.

in cross section and about 40 feet long, the tunnel forming the combustion chamber. At one end of the chamber there is a standard Murphy stoker having 25 square feet of projected grate area. The other end of the tunnel connects with the combustion chamber of a hand-fired Heine boiler, the connection being made through the side wall of the boiler furnace.

The details of the walls and the roof are also shown in figure 2. The side walls consist of two walls separated by a 2-inch air space. The inner wall is built of fire brick and is 9 inches thick. The outer wall is of common red brick and is 8 inches thick. The roof consists of two brick arches separated by a 1-inch layer of asbestos cement; the inner arch is of fire brick and is 8 inches thick; the outer arch, which is only 4 inches thick, is built of pressed red brick. Figure 3 shows two sections through the stoker and illustrates the construction of the arch over the stoker. The arch contains an air space through which air is delivered to the tuyères supplying air over the fuel bed.

In one of the side walls are a number of observation holes for measuring temperatures, spaced about 5 feet apart along the length of the furnace. In the roof three holes for sampling gases were placed opposite each hole in the side wall for temperature measurements. The position of the holes is shown in Plate I and figure 2.

The difference of pressures necessary to move the gases through the furnace was obtained by an exhaust fan and two pressure fans. The exhaust fan, which was driven by a direct-connected steam engine, was situated at the uptake of the Heine boiler. The main object of connecting the experimental furnace to the boiler was to cool the products of combustion so they could be handled by the exhaust fan. The exhaust fan could be run at a speed high enough to maintain a pressure in the uptake of $1\frac{1}{2}$ inches of water below atmospheric pressure. The pressure fan that supplied air under the grate was direct-connected to a steam engine and could maintain a pressure of 1 inch of water in the ash pit. The other pressure fan, which helped to supply air over the fuel bed through the tuyères, was a small fan directly connected to a $\frac{1}{2}$ -horsepower electric motor.

The coal was delivered from a bin to a platform built in front of and over the stoker, where, as previously stated, it was weighed as it was supplied to the stoker magazine.

METHOD OF CONDUCTING EXPERIMENTS.

During about one-half of the investigations reported in this bulletin, the experimental furnace was operated continuously for producing steam for the power plant. When not so used fire was started in it one day before running a test.

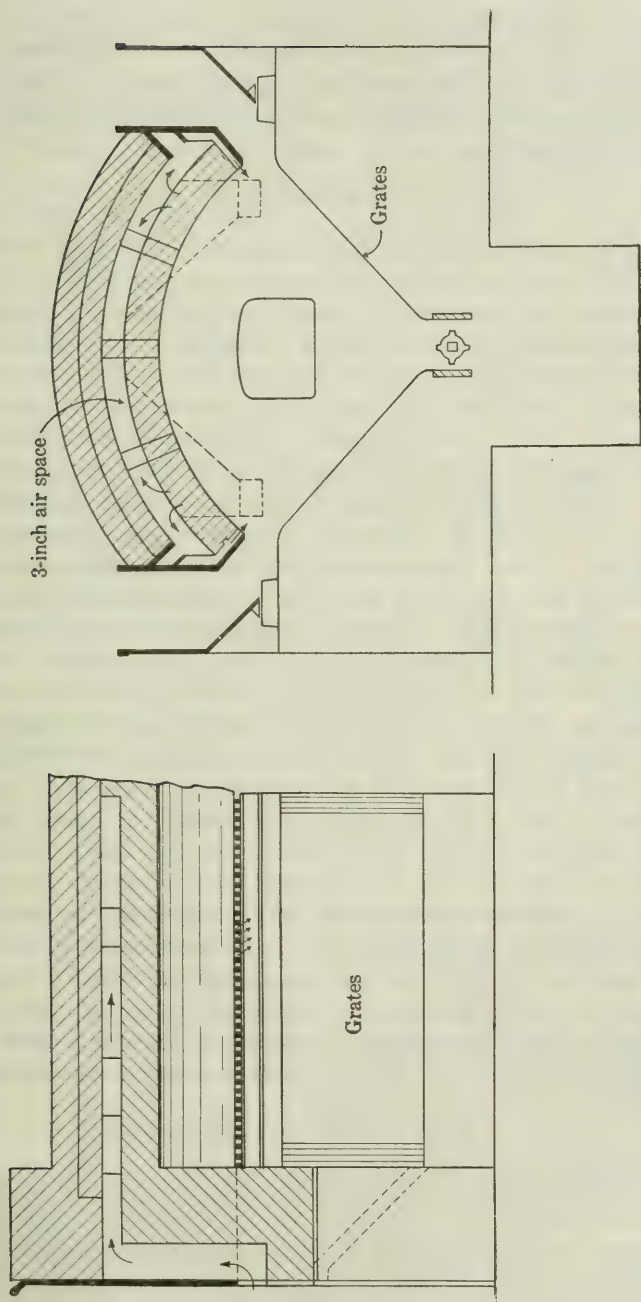


FIGURE 3.—Sections through the stoker, showing construction of the arch and method of supplying air to the tuyères.

METHOD OF STARTING AND STOPPING THE TESTS.

Each test was started at about 10 to 11 o'clock a. m. and continued until 3 to 4.30 o'clock p. m. Before the test was started the fire was cleaned and all refuse removed from the ash pit. The test was closed with the same amount of coal in the magazines as there was at the time of starting.

CONDITIONS DURING THE TESTS.

During the test the rate of combustion, the thickness of fuel bed, and the air supply were kept as constant as practicable. The rate of combustion was controlled by weighing the coal as it was supplied to the magazines and by regulating the speed of the engine driving the feeding mechanism of the stoker and the speed of the pressure fan supplying air under the grate. The air supply was controlled by observing closely an automatic CO₂ recorder. Either the Bi-meter CO₂ recorder or the Uehling CO₂ recorder^a was used for this purpose. The first few tests were controlled by analyzing samples of gases for CO₂ in rapid succession with an Orsat apparatus. The gas samples for the CO₂ recorders or the Orsat apparatus were drawn at section G (see fig. 2) of the combustion chamber, where combustion was practically complete. Gas pressures in the furnace were controlled by regulating the speed of the exhaust fan. The additional air over the fuel bed was regulated partly by the small fan supplying air to the tuyères and partly by the gas pressure (draft) over the fuel bed. When more air was needed the pressure drop through the tuyères was made greater. With very high rates of combustion and high air supply not enough air could be added over the fuel bed through the tuyères. In such instances some air was admitted over the fuel bed through the fire door, which was left partly open, and through the coal-feeding openings by keeping the coal somewhat low in the magazines. The admission of air through the fire door and through the coal magazines was unsatisfactory and much trouble was experienced in keeping the air supply constant. This method of air introduction also changed to some extent the way of mixing the gases, which change resulted in some inconsistencies in the results.

WEIGHT OF ASH AND REFUSE.

At the end of each test the fire was cleaned, the clinker and the ash accumulated in the ash pit was removed and weighed, and a sample sent to the chemical laboratory for the determination of combustible. In determining the rate of combustion the amount of

^a For description of CO₂ recorders, see Barkley, J. F., and Flagg, S. B., Instruments for recording carbon dioxide in flue gases: Bull. 91, Bureau of Mines, 1915, 60 pp.

this combustible was subtracted from the amount of combustible fired.

SAMPLING AND ANALYZING FURNACE GASES.

As the study of the process of combustion was based entirely on the composition of the gases at various sections along the path of the gases, the sampling of the gases was the most important part of the observations. The sampling of gases in the furnace is a difficult problem, because the temperature ranges from $2,000^{\circ}$ to $3,200^{\circ}$ F., and consequently the samples had to be collected with water-cooled tubes. Also the fact that the gases in the furnace at any one section are not of uniform composition necessitated taking several samples at each cross section and averaging their composition. After a number of preliminary tests it was decided to take 6 to 9 samples at each section, so that 35 to 50 samples had to be collected simultaneously. The distribution of the samples at the various cross sections is shown in figures 4, 5, and 6.

The rate of combustion and the air supply was never under perfect control, so that the composition of the gases at any one point in the furnace varied somewhat in response to the changing condition of the fire. To reduce the effect of such fluctuations the samples were collected over comparatively short periods, ranging from 8 to 40 minutes, and never over the entire test. On some of the tests duplicate samples were collected.

The gas samples were collected at eight cross sections of the combustion chamber, which were designated A to H (see fig. 2), A representing the first vertical section about 5 feet from the center of the grate. On the last series of tests with Pittsburgh coal screenings,

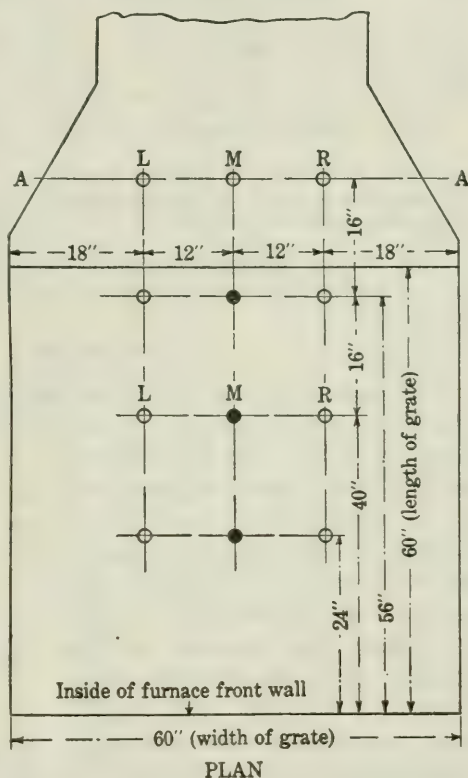


FIGURE 4.—Plan view showing position of gas and tar samplers at surface of the fuel bed and 11 inches above it. Tar-and-gas samplers are indicated by circles, and gas samplers only by dots. L, M, and R indicate left, middle, and right sampler, respectively. A indicates section A of combustion furnace.

samples of gas were also collected at three horizontal sections immediately over the grate, one being at the surface of the fuel bed, one 11 inches from the surface of the fuel bed, and the third 22 inches from the surface of the fuel bed. There were only three samplers

22 inches from the surface of the fuel bed. The position of these sections is shown in figures 4 and 7.

The sampling tubes were inserted through the vertical holes in the arch of the furnace. Two or three tubes were mounted in one water jacket, the intakes of the tubes extending to different depths in the furnace. By this construction two or three gas

samples could be taken through each hole in the roof, and the number of rubber-hose connections for the cooling water was greatly reduced.

GAS-SAMPLING TUBES.

The construction of a triple gas-sampling tube is shown in figure 8. The inlet of the sampler is connected with a half-inch hose to a water supply having a pressure of not less than 24 pounds per square inch. The discharge end of the sampler is connected in a similar way to a drain. Both hose connections are of sufficient length to permit free insertion of the sampler into the furnace or its removal while the water circulates through it. Directions for making these samplers follow:

All joints that come in contact with flames are brazed; joints that remain outside of the furnace are soldered. When the sampler is being brazed or soldered, it should be held in such a position that the molten spelter or solder runs into the joint; this is important if good joints are to be obtained. When the joints to be brazed are being fitted, care should be taken to have the end of the copper tubing extend out far enough so that the spelter will not run down into it. After the joint has been brazed, the protruding end of the copper tube can be filed off. The

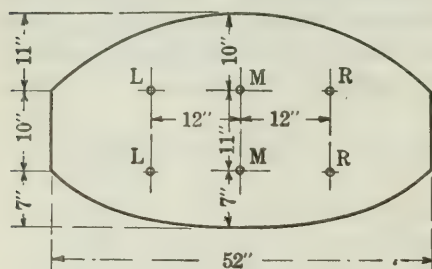


FIGURE 5.—Position of tar and gas samplers at section A of combustion furnace. L, M, and R indicate left, middle, and right sampler, respectively.

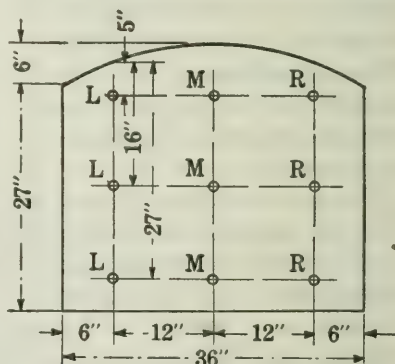


FIGURE 6.—Position of gas samplers at sections beyond section A of combustion furnace. L, M, and R indicate left, middle, and right sampler, respectively.

side outlets on the gas tubes are first fitted, as shown, and then soldered by placing a piece of solder into the side outlet and holding the joints over a gas-torch flame, so that the molten solder runs all around the joint. The hole between the side outlet and the gas tube is drilled after the joint has been soldered. The gas sample is drawn through the side outlet; the opening at the end of the gas tube is closed with a piece of rubber tubing and a glass plug, and is used only for cleaning the tube when stopped with soot.

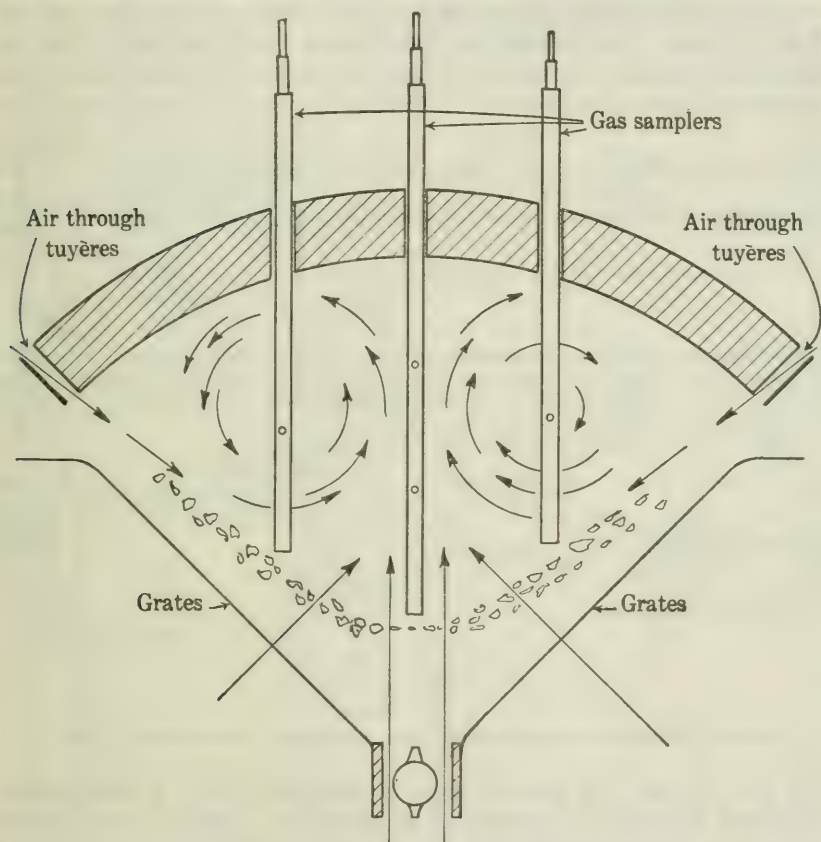


FIGURE 7.—Position of tar and gas samplers over the fuel bed. Circles indicate inlets of samplers. The two side rows took tar and soot samples; the central row, gas only. Entrance of air through tuyères and the whirling motion of the gases that is caused by it are indicated.

GAS-COLLECTING APPARATUS.

The arrangement of the apparatus for collecting gas samples is shown diagrammatically in figure 9. The apparatus consists mainly of the previously described water-cooled sampling tube, a glass gas container, a wash bottle, and a suction pipe leading to a steam ejector. By means of the suction pipe one steam ejector serves to

can be controlled by adjusting the lower valve or by attaching to it a special glass tip having the proper size of opening, which is determined by trial. The inlet of the gas container extends within about one-half inch of the bottom so that as long as the inlet remains below the surface of the mercury the mercury flows out under constant head, being replaced with gas at a uniform rate. The flow of mercury is stopped before its level falls below the inlet.

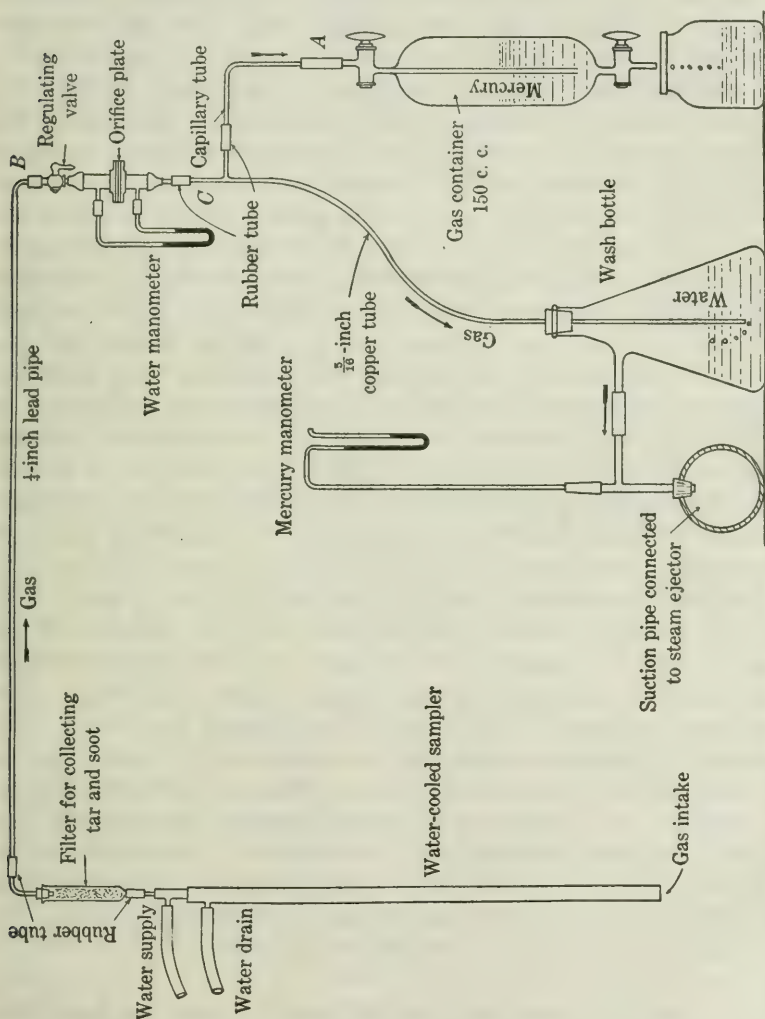


FIGURE 9.—Diagram of apparatus used in sampling gases, tar, and soot. When only gases were sampled the orifice and the filter part were removed, and the end B of the lead pipe was connected directly to the end C of the copper tube.

The gas container also serves as a safe and convenient holder for storing the samples. The mercury forms a seal between the gas and the stopcocks as long as its level does not fall below the opening of the inlet. The seal prevents leakage through the stopcocks. All danger of leakage into the container is entirely eliminated if the gas

sample is placed under slight pressure by forcing in some mercury through the gas inlet tube.

For convenience and safety in handling, three gas containers are mounted together in one portable wooden stand.

APPARATUS FOR COLLECTING SAMPLES OF SOOT AND TAR.

In the last series of tests with Pittsburgh coal screenings a number of samples of soot and tar were collected near the fuel bed with the samples of gases. Of the soot and tar samples six were collected at the surface of the fuel bed, six samples 11 inches from the fuel bed, and six at section A (see fig. 2) of the combustion chamber. The location of the soot and tar samplers is shown in figures 4, 5, and 7. The sampling tubes used for this purpose were somewhat larger than those used for sampling gas alone. The inner metal tube was three-eighths inch in external diameter. Into this tube fitted snugly a removable glass tube which extended to within three-fourths of an inch of the furnace end of the metal tube and protruded about 2 inches from the outside end, forming a lining which could be pulled out and cleaned. The outside end of the glass tube was connected to a filter consisting of a glass tube 12 inches long and three-fourths inch in diameter, filled with asbestos fiber which had been previously burned to remove all combustible material. The fiber was packed around a brass-wire spring to prevent its being drawn by the moving gases to one end of the filter tube and stopping it. No fiber was placed in the long glass tube forming the lining for the sampling tube. The soot and tar was collected partly in the long tube and partly in the filter. In order to obtain quantitative data the volume of gas drawn through the sampler and the filter was measured with small orifices placed in the pipe connection as shown in figure 9. The orifices were calibrated with a small experimental gas meter. The pressure drop through the orifices was measured with U-tube manometers connected as shown in the figure. The soot and tar samples were collected for a period of 20 to 30 minutes; the pressure drop through the orifices was read every five minutes. The readings were plotted with time as abscissa and the weight of gas was computed for small sections of the curve connecting the plotting points. The weight of the gases as thus determined is probably correct within 25 per cent.

After a sample of soot and tar had been collected the long glass tube was pulled out of the sampler, and the deposit carefully washed out with benzol. This deposit, together with that collected in the filter, was taken as the sample of tar and soot.

ANALYSIS OF GAS SAMPLES.

The analyses of gas samples were made with modified Hempel apparatus. Mercury was used in the measuring burette, which was water-jacketed and provided with a Pettersson pressure and temperature compensating tube. Absorption pipettes of the Lindstrom type, fitted with a two-way stopcock and small cup for containing water, were used. By the use of pipettes of this type the error due to the volume of gas in capillary connections is eliminated.

The samples of gas were analyzed for CO_2 , O_2 , CO , CH_4 , H_2 , and unsaturated hydrocarbons. Phosphorus was used for the determination of O_2 . CO was determined by absorption in ammoniacal cuprous chloride solution; three pipettes were used in series, care being taken that the third one always contained a fresh solution. The determinations of CH_4 and H_2 were made over mercury by the slow combustion method with heated platinum coil. The content of unsaturated hydrocarbons in the samples collected over the fuel bed and at section A was determined by the method of absorption in fuming sulphuric acid.

During the early part of this work a special burette, designed for exact analysis and described in Technical Paper 63,^a was used for the determinations of CH_4 and H_2 . Because of the difficulties of obtaining samples with sufficient accuracy to justify exact gas analysis, the use of this burette was discontinued. The determination of CO_2 , O_2 , unsaturated hydrocarbons, and small quantities of CO is within plus or minus 0.1 per cent of the volume of the sample. With large amounts of CO requiring more than one pipette for absorption, and with CH_4 and H_2 , the error may reach at times plus or minus 0.2 per cent.

DETERMINATION OF TAR AND SOOT.

Tar was separated from soot by extraction with hot benzol in Soxhlet extraction apparatus. The soluble part was considered tar and the insoluble combustible part, soot.

The tar and soot deposited in the glass sampling tube and filter were removed by cleaning thoroughly with asbestos fiber and benzol. The asbestos fiber from the filter and that used in cleaning, which together contained all the tar and soot, were placed in an alundum thimble and extracted on a sand bath until the benzol was colorless. The tar, contained in the extraction flask, was freed from benzol by passing dry air at room temperature through the flask until the loss was less than 1 milligram on successive weighings one-half hour apart. The difference between the weight of the flask with tar and that of the clean, dry flask is the weight of tar.

^a Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces: Tech. Paper 63, Bureau of Mines, 1914, p. 17.

After extraction was completed the alundum thimble containing the soot mixed with asbestos fiber was dried to constant weight at 105° to 110° C., and the soot burned off in a muffle furnace at red heat. The loss in weight of the dried thimble due to burning is the amount of soot.

The method does not yield strictly accurate results for two reasons. First, benzol combines to some extent with tar yielding insoluble compounds, thereby giving low results for tar and high results for soot.^a The error from this source is not over 5 per cent of the weight of the tar. Second, while dry air is being passed at atmospheric temperature through the flask to remove benzol, some of the light oils contained in the tar are driven off with the benzol and lost. The error from this source is not greater than 2 per cent.

TEMPERATURE MEASUREMENTS.

Observations of the temperature within the combustion chamber were made at 20-minute intervals in all the tests. The temperatures

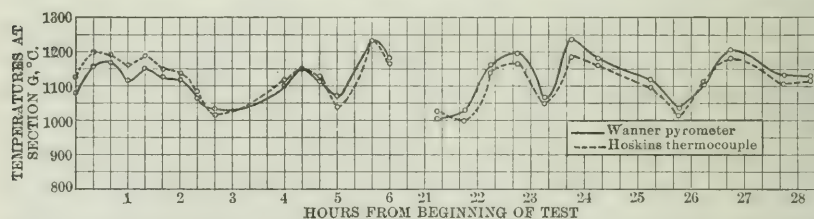


FIGURE 10.—Comparison of temperatures in combustion chamber at section G, as measured with Hoskins thermocouple and Wanner pyrometer.

were measured with a Wanner optical pyrometer through the side holes at sections A and G (see fig. 2) of the furnace and in many tests also at C and E. On account of the high temperature and the presence of slag in the gases it was not practicable to use thermocouples.

The temperature indicated by the optical pyrometer is the temperature of the inner surface of the opposite wall when there is no flame. When the chamber is filled with flame, the pyrometer measures the temperature of the flame. To determine the relation between the temperature of the wall as indicated by the optical pyrometer and the temperature indicated by a thermocouple suspended in the path of gases, a Hoskins thermocouple was placed at section G with its hot junction in the center of the section, and simultaneous readings were made with the couple and the optical pyrometer. The results are given in figure 10. As shown in the figure the two methods of temperature measurements agree within about 25° C. This relation

^a Weiss, J. M., Free carbon; its nature and determination in tar products: Jour. Ind. and Eng. Chem., vol. 6, 1914, p. 279.

was determined only for readings that were taken when there was no flame present and the gases were transparent. Usually the gases leaving the fuel bed carry with them in suspension soot, tar, and a small amount of ash. When present in large quantities these substances form an opaque cloud of flame which obscures the wall beyond, and as the individual particles are incandescent, it is the temperature of the cloud or flame that is measured by the optical pyrometer and not the temperature of the gases or of the wall. As the particles of soot are hot from their own combustion, besides receiving heat from the surrounding gases, it is by no means certain that the temperature measured by the optical pyrometer is the average temperature of the gases and flame passing through the combustion chamber.

GAS-PRESSURE MEASUREMENTS.

Readings of gas pressures were taken at 20-minute intervals on all the tests. The pressures recorded were those in the ash pit and at sections A and G of the furnace. Ellison inclined-tube draft gages were used for this purpose.

COALS USED IN THE TESTS.

As previously stated, three kinds of coal were used in the tests, namely, Pocahontas, Pittsburgh, and Illinois coal.

The Pocahontas coal used was from the Norfolk mine of the Pocahontas Consolidated Coal Co., at Vivian, W. Va., which works the Pocahontas No. 3 bed. The average analysis of two car loads of the coal is given in column 2, Table 1 (p. 24). The coal was screened at the mine by passing it over a $\frac{3}{4}$ -inch and through a $1\frac{1}{2}$ -inch bar screen. In the necessary handling the size of the coal was somewhat reduced. Actual sizing tests with wire screens showed the sizes given in column 2, Table 2.

The Pittsburgh coal used came from the No. 4 mine of the Jamison Coal & Coke Co., situated 4 miles north of Greensburg, Westmoreland County, Pa. The average analysis of the car samples is given in column 3, Table 1. The coal was shipped as run-of-mine and had to be broken to the desired size before using. Column 3, Table 2, gives the percentage of the different sizes of the coal as burned. The sizes were determined by running over shaking screens samples of coal from several tests.

The Illinois coal came from bed No. 6, and was mined in the Vermilion mine of the Bunsen Coal Co., at Georgetown, Vermilion County. The analysis of the coal is given in column 4, Table 1. The coal was shipped as run-of-mine and was broken with a hammer before using it. The sizes of the coal as it was burned are given in column 4, Table 2.

In the last series of 23 tests, Pittsburgh coal screenings similar in composition to the Pittsburgh run-of-mine coal (column 3, Table 1) were used. These screenings, used as regular fuel for the power plant of the experiment station, varied greatly in size, the largest pieces being about 2 inches across. On the average about one-third of the coal would run through a $\frac{1}{4}$ -inch screen. This series of tests was undertaken with the object of studying the combustion between the surface of the fuel bed and section A of the furnace. The greater part of the combustible rising from the fuel bed is burned in this space, as shown in figure 13.

TABLE 1.—*Analysis of coals used in the tests.*

PROXIMATE ANALYSIS OF COAL AS RECEIVED.

Constituent.	Poca- hontas coal.	Pitts- burgh coal.	Illinois coal.
Moisture.....per cent..	2.21	2.51	16.16
Volatile matter.....do..	15.78	30.28	34.09
Fixed carbon.....do..	71.65	56.82	39.19
Ash.....do..	10.36	10.39	10.56
	100.00	100.00	100.00

ULTIMATE ANALYSIS OF DRY COAL.

Hydrogen.....per cent..	3.92	4.82	4.66
Carbon.....do..	80.90	76.57	69.63
Nitrogen.....do..	1.06	1.55	1.49
Oxygen.....do..	2.97	4.99	9.55
Sulphur.....do..	.56	1.41	2.08
Ash.....do..	10.59	10.66	12.59
	100.00	100.00	100.00
Calorific value per pound, as received.....B. t. u..	13,702	13,365	10,433

TABLE 2.—*Sizes of coal as burned.*

[Square holes in screen.]

Size of coal.	Per cent by weight.		
	Poca- hontas.	Pitts- burgh.	Illinois.
Through $\frac{1}{4}$ -inch mesh.....	5	10	16
Over $\frac{1}{4}$ -inch and through $\frac{1}{2}$ -inch mesh.....	5	8	12
Over $\frac{1}{2}$ -inch and through $\frac{3}{4}$ -inch mesh.....	6	14	21
Over $\frac{3}{4}$ -inch and through 1-inch mesh.....	62	23	27
Over 1-inch and through $1\frac{1}{4}$ -inch mesh.....	22	45	24
	100	100	100

METHOD OF SAMPLING.

A car sample was taken at the time of unloading the cars and sent to the chemical laboratory for proximate and ultimate analysis and determination of heat units. During each test a sample of about

100 pounds was collected and a part of it submitted for proximate analysis. A sample of ash and refuse was collected at the close of each test for the determination of the percentage of combustible.

RESULTS OF THE EXPERIMENTS.

In all, 100 tests with complete sets of observations were made. Of these, 23 tests were with Pocahontas run-of-mine coal, 37 with Pittsburgh run-of-mine coal, 17 with Illinois run-of-mine coal, and 23 with Pittsburgh screenings. With each coal, tests were run at rates of combustion of 20, 30, 40, 50, and 60 pounds of coal per square foot of grate per hour. A series of three or more tests was run with each rate of combustion, the tests in any one of these series being run with different air supply. Thus there were investigated three factors—the kind of coal, the rate of combustion, and the air supply.

VARIATION OF CONDITIONS DURING TESTS.

Notwithstanding the provisions made in designing the apparatus and the care taken in its operation, conditions varied considerably during the tests. These variations are shown graphically in figures 11 and 12. Perhaps the most serious variation affecting the results of the tests is that of the percentage of CO_2 in the furnace gases. This variation seems inherent with the stoker, as the coal on the upper part of the stoker caked instead of sliding down uniformly. On account of this caking, bare spots frequently appeared below the crusted area; the crust had to be broken and the holes covered with coal brought down with a hand tool. These holes and the work of covering them caused irregular air supply and resulting variation of CO_2 in the gases. The change in temperature along the chamber is due to heat absorption by the gas samplers and other causes explained in the discussion of temperature variation in pages 109 to 111.

Experiments made on a large scale approximating commercial conditions are subject to variations that do not occur in small laboratory apparatus in which the conditions of operation can be more accurately controlled. Tests with small laboratory apparatus have the drawback that one is never sure to what extent the results obtained are applicable to commercial types of furnaces. In choosing apparatus for experiment one has the alternative of equipment of nearly commercial type and size with large variation of operating conditions, or a small furnace with controllable conditions giving accurate results, which, however, may not be applicable to furnaces of commercial size.

TABULATED RESULTS.

The results of the test are given in Table 3 and are arranged as follows: (1) The tests are grouped according to the kind of coal used; (2) tests with the same kind of coal are grouped according to the rate

of combustion; and (3) the tests with nearly the same rate of combustion are arranged according to the air supply.

On tests 104 to 113, inclusive, of the series with Pocahontas coal, duplicate sets of gas samples were collected. The sets are denoted as

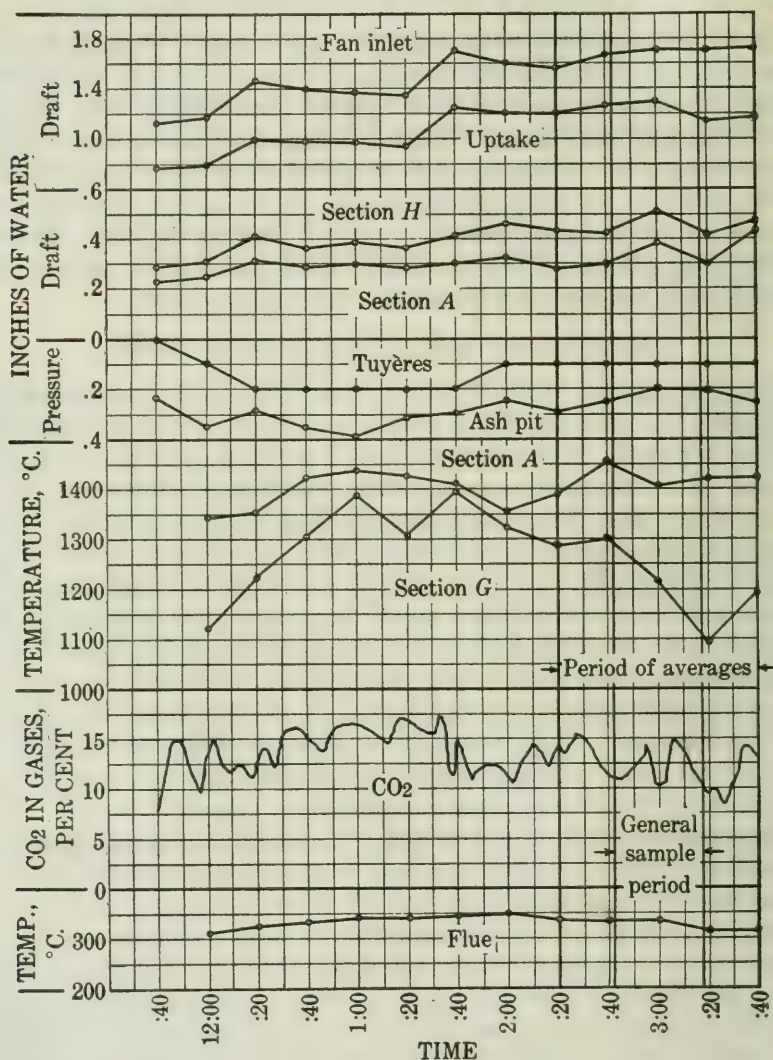


FIGURE 11.—Variation of conditions and period of sampling in test 179.

104-1, 104-2, 105-1, 105-2, etc. In tests with the Pittsburgh screenings, 12 to 21 gas samples were taken at sections in front of section A of the combustion chamber. At these sections and at section A were collected also 18 soot and tar samples.

In Table 3 the tests are grouped according to the kind of coal used in the tests. Column 1 gives the serial number of the test and

column 2 the weight of coal fired per square foot of grate per hour. The figures given in this column were obtained by dividing the total weight of coal by the length of test in hours given in column 3, and by 25, which is the projected area of the grate in square feet.

Column 3 gives the time of starting and stopping the test, from which may be obtained the total length of test in hours. This includes the

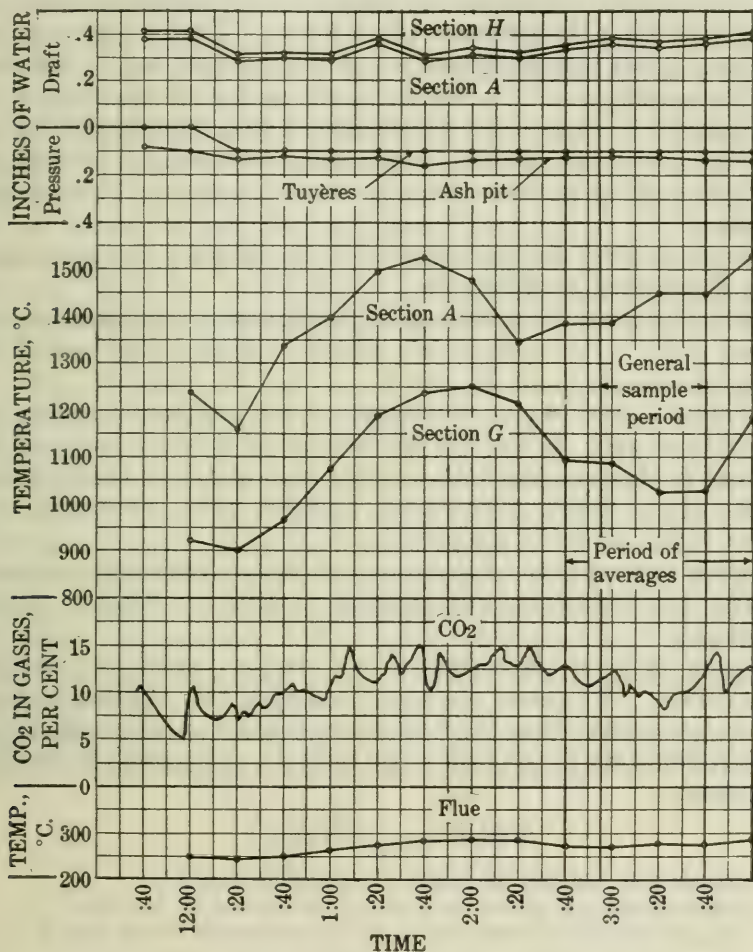


FIGURE 12.—Variations of conditions and period of sampling in test 173.

entire period during which coal was weighed and burned at the desired rate.

Column 4 gives the length of the part of the test used for obtaining the averages of gas pressures and temperatures. This period started 30 to 60 minutes before the collection of gas samples was begun, and ended 30 to 60 minutes after the collection of gas samples was completed.

Column 5 gives the period during which the samples of gas were collected. The three different periods of columns 3, 4, and 5 are indicated in figures 11 and 12.

Column 6 shows in what section of the furnace the gas samples were collected. The situation of the sections is shown in figures 2, 4, 5, 6 and 7. In the series of tests with Pittsburgh screenings the two figures above A, column 6, indicate the distance in inches of the intake of the sampler from the surface of the fuel bed. Thus, 0 indicates that the sampler was just at the surface of the fuel bed, and 11 indicates that the sampler was 11 inches above the surface of the fuel bed.

Columns 7 to 12 give the percentages of CO_2 , unsaturated hydrocarbons, O_2 , CO , CH_4 , and H_2 in the gases, as determined by analysis. The figures given in these columns are the averages of six to nine samples.

Column 13 gives the percentage of N_2 in the gases, this percentage being determined by difference.

Column 14 gives the percentage of total gaseous combustible in the furnace gases. The value in this column is equal to the sum of the values in columns 8, 10, 11, and 12.

Columns 15 and 16 give the weights of tar and soot in grams per cubic foot of gas. The values are determined from the soot and tar collected in the sampling tube and the filter and from the measured volume of gas drawn through the sampler. The determination is correct within about 25 per cent.

Column 17 shows the temperatures at sections indicated in column 6. The temperatures were determined with a Wanner optical pyrometer.

Column 18 gives the weight of air used in burning 1 pound of combustible. The values are calculated from the analyses of gases collected at section G or H of the furnace and from the composition of the combustible in the coal. The weight is calculated by means of the formula:

$$W = 3.03 C \left(\frac{\text{N}_2}{\text{CO}_2 + \text{CO} + \text{CH}_4} \right).$$

W =pounds of air supplied per pound of combustible burned.

C =Weight of carbon in pounds per pound of moisture and ash free coal.

N_2 , CO_2 , CO , and CH_4 =percentages in the furnace gases at section G or H.

The amount of combustible burned is equal to the amount fired minus the amount of combustible in the refuse.

Column 19 gives the excess of air used in the combustion, expressed in percentage of the weight of air theoretically needed to completely burn 1 pound of combustible. The excess is equal to the weight of air actually supplied to the furnace minus the weight theoretically needed. The excess air is expressed as a percentage of the weight theoretically required. The weight of air theoretically required is

computed by means of the formula, $A = 34.48H + 11.58C + 4.336(S - O)$, in which H, C, S, and O are the percentages of hydrogen, carbon, sulphur, and oxygen in moisture and ash free coal. The formula is not exact, because (1) it rests on the assumption that the composition of the combustible matter in the refuse is the same as the composition of the moisture and ash free coal fired; (2) no correction is made for the combustible matter that may be carried away with the furnace gases as tar and soot; and (3) no correction is made for the nitrogen in the coal. The assumption that the composition of the combustible matter in the refuse is the same as the composition of the moisture and ash free coal is obviously not correct, the combustible in the refuse being largely carbon with very little volatile matter in it. Consequently the weight of carbon in the furnace gas per pound of combustible burned is somewhat less than the value C, which is obtained from the ultimate analysis of the coal. The error from this assumption regarding the combustible matter in the refuse is probably not over 1 per cent, as was shown in Technical Paper 63.^a

Column 20 gives the pressure of air in the ash pit in inches of water above the atmospheric pressure. Column 21 gives the pressure of gases over the fuel bed in inches of water below the atmospheric pressure. The values in these columns are each the average of a number of readings obtained either with an Ellison inclined tube draft gage or with a recording "hydro" gage.

Column 22 gives the pressure of the gases at section H in the combustion chamber and column 23 the pressure of the gases in the uptake of the Heine boiler. The values given in these columns are each the average of a number of readings obtained with an Ellison draft gage. The table follows.

^a Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces, a preliminary report: Tech. Paper 63, Bureau of Mines, 1914, p. 30.

108-1	22.0	8.48 a. m. to 3.50 p. m.	1.40 to 3.40 p. m.	2.07 to 2.13 p. m.	A 13.4 B 14.1 C 13.2 D 14.2 E 14.2 F 14.4 G 14.1 H 12.9	6.0 5.3 5.3 5.2 4.3 5.0 5.3 5.3	.7 0 7 0 6 0 0 0	1,540	.04	.11	.14
109-2	20.0	10 a. m. to 3 p. m.	1.20 to 3 p. m.	2.12 to 2.18 p. m.	A 7.3 B 6.9 C 8.6 D 8.6 E 8.4 F 8.5 G 8.6 H 8.4	10.2 12.4 11.0 10.8 11.0 11.0 11.0 11.0	3.5 3 0 0 0 0 0 0	1,342	.0	.11	.15
109-1	20.0	10 a. m. to 3 p. m.	1.20 to 3 p. m.	1.50 to 1.55 p. m.	A 8.3 B 6.8 C 7.5 D 9.1 E 8.3 F 8.1 G 8.1 H 7.7	10.6 11.6 10.6 11.3 11.2 11.7 11.7 11.7	.8 3 1 0 0 0 0 0	1,344	.0	.15	.11
106-1	28.0	11 a. m. to 4.40 p. m.	2.40 to 4.20 p. m.	3.05 to 3.10 p. m.	A 11.5 B 15.0 C 16.4 D 16.4 E 16.0 F 15.8 G 16.3 H 14.9	2.2 2.5 1.9 2.6 2.8 3.6 2.9 2.9	8.4 1.0 2 0 0 0 0 0	1,625	.15	.11	.15
106-2	28.0	11 a. m. to 4.40 p. m.	2.40 to 4.20 p. m.	3.57 to 4.03 p. m.	A 13.9 B 15.3 C 15.1 D 15.2 E 15.6 F 15.4 G 15.4 H 14.2	2.2 3.3 4.0 3.7 3.3 3.8 3.8 3.8	5.0 1 0 0 0 0 0 0	1,625	.15	.11	.15
105-2	28.0	11 a. m. to 4 p. m.	1.20 to 4 p. m.	3.25 to 3.32 p. m.	A 13.0 B 13.1 C 13.9 D 13.4 E 13.5 F 13.5 G 13.3 H 14.4	2.5 2.7 3.2 3.9 3.5 3.7 4.0 4.0	5.7 4 0 0 0 0 0 0	1,594	.11	.10	.15

a See figure 2 for diagram of furnace, showing sections A to H.

[illegible]

[illegible]

TABLE 3.—Results of combustion tests—Continued.

POCAHONTAS COAL—Continued.

Test No.	(Coal fired per square foot of grate area per hour.	Duration of test.	Period used for obtaining averages of gas temperatures and pressures.	Period of gas sampling.	Section of furnace where samples were taken.	Average composition of gases, by volume.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature. ° C.	Weight of air per pound of combustible.	Excess of air.	Gas pressure, inches of water.														
						CO ₂	Unsat- urated hy- drocarbons.	O ₂	CO.	CH ₄	H ₂	N ₂	Total gaseous combustible.						In ash pit, above atmospheric.	(Over fuel bed, be- low atmospheric.	At rear of cham- ber, below at- mospheric.	In uptake, below atmospheric.											
116	42.8	11 a. m. to 4.20 p. m.	3 to 4.20 p. m.	3.33 to 3.39 p. m.	5	6	P. ct.	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23									
							A	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Gms.										Gms.	Lbs.	P. ct.	0.15	0.12	0.18			
							B	11.2	8.9	1.9	6.0	1	1.4	77.2	7.5												1,302	21.3	78.9				
							C	11.5	7.8	2.2	2.8			79.5	3.5												1,618			.51	.26	.44	
							D	11.4	7.1	1.1	1.3	1	4	79.9	1.8																		
							E	11.6	7.6	.0	1.5	2	0	80.9	.9																		
							F				7	2	0	81.9	.6																		
							G				1.0	1	0	80.9	.6												1,475	12.9	7.3				
121	61.0	11 a. m. to 3.20 p. m.	12.40 to 3.20 p. m.	2.01 to 2.07 p. m.	5	6	H	17.2	1.4	1	1	0	81.1	.3		15	16	17	18	19	20	21	22	23									
							A	14.3	1.0	6.0	1	1.4	77.2	7.5												1,302	21.3	78.9					
							B	15.8	1.2	2.8				79.5	3.5												1,618			.51	.26	.44	
							C	16.3	2.0	1.3	1	4	79.9	1.8																			
							D	16.9	1.3	1.5	2	0	80.9	.9																			
							E	17.0	1.0	7	2	0	81.9	.6																			
							F	17.5	1.0	1	0	5	80.9	.6																			
							G	17.6	1.8	2	2	1	0	81.1	.3												1,475	12.9	7.3				
120	55.7	11 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.49 to 2.56 p. m.	5	6	A	13.7	2.5	5.5	2	1	1	77.0	6.8	15	16	17	18	19	20	21	22	23									
							B	15.9	1.8	1.9				78.8	2.4												1,549			.43	.32	.47	
							C	15.5	3.0	.8	2	1	4	80.4	1.1																		
							D	15.0	3.3	.3	0	0	81.4	.3																			
							E	15.7	2.8	.0	0	0	81.5	.0																			
							F	15.7	2.8	.1	1	0	81.3	.2																			
							G	16.1	2.4	.1	0	0	81.3	.2																			
							H	15.9	2.8	.2	0	0	81.1	.2													1,436	13.9	15.5				

124	58.9	11 a. m. to 3.20 p. m.	2 to 3.20 p. m.	2.34 to 2.41 p. m.	A B C D E F G H	12.3	6.3	2.0	.2	79.0	2.4	1,560	.48	.26	.39
						13.1	6.3	.1	.0	80.5	.1				
						12.8	6.6	.0	.0	80.6	.0				
123	58.2	11 a. m. to 3.40 p. m.	1.20 to 3.40 p. m.	2.25 to 2.32 p. m.	A B C D E F G H	11.1	8.4	.0	.0	80.5	.0	1,318	66.3		
						13.0	5.7	1.9	.1	79.1	2.2	1,523		.49	.23
						13.0	6.8	.0	.0	80.0	.2				.38
						11.4	8.2	.0	.0	80.4	.0				
125	66.5	11.40 a. m. to 3.20 p. m.	2.20 to 3.20 p. m.	2.45 to 2.53 p. m.	A B C D E F G H	10.4	9.4	.0	.0	80.2	.0	1,244	21.3	76.8	
						10.6	3.8	8.2	.2	75.8	9.8	1,599		.55	.30
						14.9	2.0	3.3	.2	79.2	3.9				.50
						14.3	3.9	1.1	.1	80.3	1.4				
						15.3	2.0	1.7	.0	80.7	1.4				
						15.3	2.3	.0	.0	81.5	.0				
						16.4	5.4	.4	.0	81.0	.5	1,386			
						13.5	2.4	.1	.0	80.6	.5		13.2	10.1	

PITTSBURGH RUN-OF-MINE.

149	22.3	11 a. m. to 3.40 p. m.	1.40 to 3.40 p. m.	2.09 to 2.19 p. m.	A B C D E F G H	12.4	3.6	6.0	0.0	76.4	7.6	1,554		0.06	0.09	0.10
						14.1	3.3	2.0	.0	79.7	2.9					
						15.0	2.5	1.6	.0	80.0	2.5					
						14.8	3.0	1.1	.0	80.5	1.7					
						14.9	2.6	1.5	.0	80.2	2.3					
						14.9	3.1	1.0	.0	80.3	1.7					
						13.6	4.8	1.2	.0	78.8	1.8	1,352				
						15.2	3.1	.7	.0	80.7	1.0		13.2	14.0		
155	19.6	11 a. m. to 2.40 p. m.	12.40 to 2.40 p. m.	1.41 to 1.48 p. m.	A B C D E F G H	11.1	2.4	10.4	.0	73.3	13.2	1,679		.07	.10	.11
						14.6	2.3	1.7	.0	80.0	2.4					
						14.9	3.5	.0	.0	80.8	.8					
						15.5	3.6	.1	.0	81.2	.1					
						14.5	3.9	.0	.0	81.5	.0					
						15.4	3.3	.0	.0	81.3	.0	1,433				
						15.2	3.4	.0	.0	81.2	.0					
						15.6	3.9	.0	.0	81.2	.0		13.5	16.3		

156	40.0	11.20 a. m. to 3.20 p. m.	1.20 to 3.20 p. m.	1.44 to 2.59 p. m.	A 10.9	5.8	5.0	0	1.2	77.1	6.2	1,546			.09	.32	.38
					B 12.1	6.5	8.8	0	.3	80.3	1.1						
					C 12.4	6.3	5.0	0	.1	80.7							
					D 12.1	6.7	2.0	0	.1	80.9	3						
					E 12.5	6.0	4.0	0	.1	81.0	5						
					F 12.4	6.4	2.0	0	.0	81.0	2						
					G 12.2	6.7	1.0	0	.0	81.0	1	1,268					
					H 12.6	6.4	1.0	0	.0	80.9	1		16.5	42.5			
132	38.7	10.30 a. m. to 3.40 p. m.	2.20 to 3.40 p. m.	2.58 to 3.05 p. m.	A 12.0	4.7	4.1	2	1.4	77.6	5.7	1,535			.23	.19	.27
					B 13.7	4.6	8.8	1	.5	80.3	1.4						
					C 13.6	5.0	1.0	0	.0	81.3	1						
					D 13.0	5.9	0.0	0	.0	81.1	0						
					E 13.2	5.4	0.0	0	.0	81.4	0						
					F 11.8	5.6	0.0	0	.1	82.5	1						
					G 12.9	5.5	2.0	0	.0	81.4	2	1,239					
					H 12.6	6.4	0.0	0	.0	81.0	0		16.7	44.1			
135	44.9	10.30 a. m. to 3.40 p. m.	2.20 to 3.40 p. m.	2.55 to 3.02 p. m.	A 12.8	5.2	2.3	1	.7	78.9	3.1	1,602			.34	.20	.31
					B 11.1	4.6	2.1	0	.1	80.8	5						
					C 13.9	4.9	0.0	0	.1	81.1	1						
					D 13.4	5.5	0.0	0	.0	81.1	0						
					E 11.5	5.4	0.0	0	.0	81.1	0						
					F 13.8	5.4	0.0	0	.0	81.2	0						
					G 13.2	5.3	0.0	0	.0	81.5	0	1,293					
					H 12.3	6.7	0.0	0	.0	81.0	0		17.1	47.3			
129	39.2	10.30 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.48 to 2.55 p. m.	A 11.5	5.4	3.5	0	.9	78.7	4.1	1,604			.22	.18	.27
					B 13.4	4.8	7.7	1	.1	80.9	0						
					C 13.3	5.3	0.0	0	.0	81.4	0						
					D												
					E												
					F												
					G												
					H 12.1	6.8	0.0	0	.0	81.1	0	1,320					
158	40.0	11.20 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.09 to 3.24 p. m.	A 10.2	5.7	6.1	0	1.3	76.7	7.1	1,526			.13	.34	.37
					B 11.5	7.1	5.0	0	.1	80.8	6						
					C 11.6	7.2	4.0	0	.1	80.7	5						
					D 11.4	7.6	3.0	0	.0	80.7	3						
					E 11.6	7.2	1.0	0	.0	81.1	1						
					F 11.5	7.4	1.0	0	.0	81.0	1						
					G 11.1	8.0	1.0	0	.0	80.8	1	1,223					
					H 11.4	7.7	1.0	0	.0	80.8	1		18.2	57.1			
131	38.4	8 to 11.20 a. m.	10 to 11.20 a. m.	10.39 to 10.46 a. m.	A 11.7	7.8	1.6	1	.4	78.4	2.1	1,416			.16	.26	.35
					B 11.9	6.8	9.1	1	.2	80.1	1.2						
					C 12.0	7.0	3.3	1	.1	80.5	5						
					D 11.0	8.3	0.0	0	.0	80.7	0						
					E 11.9	7.3	0.0	0	.0	80.8	0						
					F 13.0	7.2	0.0	0	.0	79.8	0						
					G 12.8	6.5	0.0	0	.0	80.7	0	1,058					
					H 10.3	9.2	0.0	0	.0	80.5	0		20.3	75.1			

153	60.0	11 a. m. to 2.40 p. m.	1.20 to 2.40 p. m.	1.53 to 2 p. m.	A 12.2 B 12.4 C 13.0 D 12.1 E 12.5 F 12.1 G 12.6 H 12.4	6.1 6.2 6.0 7.1 6.5 6.6 6.2 6.6	2.1 5 0 0 0 0 0 0	0 0 0 0 0 0 0 0	.6 79.0 2.7	1,632	.52 .32 .41	
163	56.7	11.40 a. m. to 3.20 p. m.	2 to 3.20 p. m.	2.13 to 2.59 p. m.	A 9.0 B 11.6 C 10.2 D 11.8 E 12.2 F 11.7 G 12.1 H 12.1	5.4 6.5 9.1 7.2 7.0 7.3 6.9	9.6 1.6 2 2 1 1 1	0 0 0 0 0 0 0 0	2.6 73.4 12.2 1.9 0 80.5 2	1,505	.45 .46 .51	
142	56.5	11 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.45 to 2.52 p. m.	A 12.6 B 12.5 C 12.8 D 12.1 E 12.5 F 12.4 G 12.0 H 11.7	5.5 6.2 6.1 6.7 6.3 6.4 6.7 7.3	1.0 1 0 0 0 0 0 0	.4 80.5 1.4	1,753	.49 .31 .42		
139	56.8	10.20 a. m. to 3.20 p. m.	2 to 3.20 p. m.	2.33 to 2.41 p. m.	A 11.6 B 13.6 C 13.2 D 12.2 E 12.6 F 12.1 G 12.1 H 11.5	3.8 5.4 5.5 6.7 6.4 6.9 7.1 7.9	7.1 0 0 0 0 0 0 0	1.5 75.9 8.7	1,551	.46 .34 .46		
141	57.3	9 a. m. to 1.20 p. m.	12 to 1.20 p. m.	12.41 to 12.48 p. m.	A 11.1 B 10.8 C 10.4 D 9.7 E 10.3 F 10.2 G 10.0 H 9.4	6.2 8.6 8.9 9.6 8.9 9.1 9.3 10.0	3.8 0 0 0 0 0 0 0	6 78.3 4.4	1,644	.42 .32 .47		

TABLE 3.—Results of combustion tests—Continued.
ILLINOIS COAL.

Test No.	Coal fired per square foot of grate area per hour.	Duration of test.	Period used for obtaining averages of gas temperatures and pressures.	Period of gas sampling.	Section of furnace where samples were taken.	Average composition of gases, by volume.										Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature. ° C.	Weight of air per pound of combustible.	Excess of air.	Gas pressure, inches of water.						
						CO ₂	Unsaturated hydrocarbons.	O ₂	CO.	CH ₄	H ₂	N ₂	Total gaseous combustible.	In ash pit, above atmospheric.	Over fuel bed, below atmospheric.						At rear of chamber, below atmospheric.	In uptake, below atmospheric.					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23					
	Lbs.					P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Gms.	Gms.		Lbs.	P. ct.	0.0	0.12	0.14						
166	23.0	11.40 a. m. to 3.40 p. m.	2.20 to 3.40 p. m.	2.36 to 3.21 p. m.	A B C D E F G H	7.7		6.5	8.9	0.1	2.3	74.5	11.3														
						11.2		6.3	2.0	0	0.7	79.8	2.7														
						12.7		5.0	1.2	0	0.4	80.7	1.6														
						12.3		6.1	0.4	0	0.1	81.1	0.5														
						13.4		4.9	0	0	0	81.7	0														
						13.3		5.2	1.1	0	0	81.4	1.1														
						13.4		5.1	1.1	0	0	81.4	1.1														
						13.3		5.2	1.1	0	0	81.4	1.1					11.7	37.3								
168	20.0	11.40 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.24 to 3.09 p. m.	A B C D E F G H	9.2		9.6	1.5	0	0.3	79.4	1.8			1.332			0	0.13	0.15						
						10.4		8.4	0.9	0	0.2	80.1	1.1														
						10.6		8.3	0.4	0	0	80.7	0.2														
						10.6		8.5	0.2	0	0	80.7	0.2														
						10.9		8.3	1.1	0	0	80.7	1.1														
						11.2		7.9	1.1	0	0	80.8	1.1														
						10.8		8.4	0	0	0	80.8	0														
						11.2		7.9	1.1	0	0	80.8	1.1														
167	19.6	11.40 a. m. to 3.20 p. m.	1.40 to 3.20 p. m.	2.08 to 2.53 p. m.	A B C D E F G H	8.3		8.6	5.1	0	1.6	76.4	6.7			1.306			0	0.11	0.13						
						9.6		9.6	0.4	0	0.1	80.3	0.5														
						9.8		9.6	1.1	0	0	80.5	1.1														
						9.0		10.6	0	0	0	80.4	0														
						9.6		9.8	0	0	0	80.6	0														
						9.6		9.9	0	0	0	80.5	0														
						9.6		10.2	0	0	0	80.5	0														
						9.5		9.9	0	0	0	80.6	0														

165	28.3	11.20 a. m. to 3.20 p. m.	2 to 3.20 p. m..	2.19 to 3.02 p. m.	A 11.8 B 13.2 C 12.4 D 12.4 E 14.3 F 15.5 G 15.2 H 15.9	5.2 4.0 4.0 3.2 3.2 1.3 2.3 1.9 1.9	3.6 2.6 3.2 1.8 2.3 1.4 1.3 1.0	.1 0 0 0 0 0 0 0	1.2 78.1 79.3 79.0 80.1 79.9 80.6 80.6 80.8	4.9 3.5 4.6 2.4 3.3 1.9 2.0 1.4	1.477	.02 .10 .13	
166	31.6	11.40 a. m. to 3.20 p. m.	1.40 to 3.20 p. m.	2.05 to 2.50 p. m.	A 11.9 B 13.2 C 13.9 D 14.2 E 14.8 F 15.2 G 15.3 H 15.3	4.6 3.7 3.3 3.3 2.7 2.6 2.4 2.4	3.9 2.9 2.2 1.7 1.6 1.1 1.1	0 0 0 0 0 0 0	1.4 78.2 79.2 79.8 80.2 80.4 80.8 80.9	5.3 3.9 3.0 2.3 2.1 1.4 1.4	1.441	.08 .13 .20 0.30	
169	30.0	11.40 a. m. to 3.40 p. m.	2 to 3.40 p. m..	2.26 to 3.13 p. m.	A 9.5 B 12.1 C 12.7 D 12.4 E 12.9 F 12.8 G 12.9 H 12.4	7.0 6.4 6.1 6.6 6.0 6.3 6.1 6.6	5.4 1.0 1.0 1.1 1.0 1.0 1.0 1.0	1 0 0 0 0 0 0	1.8 76.2 80.2 80.7 80.9 81.0 81.0 81.0	7.3 1.3 1.5 1.1 0 0 0	1.424	.08 .15 .18	
170	30.0	11.40 a. m. to 3.40 p. m.	2 to 3.40 p. m..	2.30 to 3.15 p. m.	A 8.8 B 9.6 C 9.9 D 9.5 E 9.5 F 9.9 G 9.5 H 9.7	8.4 9.7 9.6 9.9 9.9 9.4 9.4 9.6	4.4 1 1 0 0 0 0 0	0 0 0 0 0 0 0	9 77.5 80.2 80.6 80.6 80.7 80.8 80.7	5.3 1 1 0 0 0 0	1.399	.06 .23 .26	
172	39.0	11.40 a. m. to 3.40 p. m.	2 to 3.40 p. m..	2.28 to 3.13 p. m.	A 10.2 B 12.6 C 13.2 D 13.2 E 13.8 F 14.1 G 14.4 H 14.4	6.6 5.0 4.2 4.9 4.4 4.6 4.0 4.0	4.6 2.4 1.3 1.8 7 2 1 1	1 0 0 0 0 0 0	2.2 76.3 79.2 80.7 80.8 81.0 81.0 81.0	6.9 3.2 1.9 1.1 0 0 0	1.467	.14 .29 .31	
171	33.1	11.40 a. m. to 3.20 p. m.	1.40 to 3.20 p. m.	2.03 to 2.47 p. m.	A 8.3 B 10.5 C 11.6 D 11.7 E 12.0 F 12.1 G 11.9 H 12.0	7.4 7.4 7.1 7.2 7.0 6.9 6.9 7.0	7.5 2.0 1.7 1.3 1.1 1.1 1.1 1.1	1 0 0 0 0 0 0	2.6 74.1 79.4 80.4 80.8 80.9 81.0 80.9	10.2 2.7 9 3 1 2 1 1	1.376	.11 .29 .31	

TABLE 3.—*Results of combustion tests—Continued.*

PITTSBURGH SCREENINGS.

Test No.	Coal fired per square foot of grate area per hour.	Duration of test.	Period used for obtaining averages of gas temperatures and pressures.	Period of gas sampling.	Section of furnace where samples were taken.	Average composition of gases, by volume.										Temperature.	Weight of air per pound of combustible.	Excess of air.	Gas pressure, inches of water.			
						CO ₂	Unsaturated hydrocarbons.	O ₂	CO.	CH ₄	H ₂	N ₂	Total gases combustible.	Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.				In ash pit, above atmospheric.	Over fuel bed, below atmospheric.	At rear of chamber, below atmospheric.	In uptake, below atmospheric.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
195	24.0	11 a. m. to 4 p. m.	2.40 to 4 p. m.	3.10 to 3.32 p. m.	O	P. ct. 8.9	P. ct. 0.1	P. ct. 1.2	P. ct. 14.6	P. ct. 0.6	P. ct. 5.7	P. ct. 68.9	P. ct. 21.0	Gms. 0.054	Gms. 0.180	° C.	Lbs. P. ct.	P. ct.	0.07	0.11	0.14	0.20
						A 11	10.8	2.5	8.6	-2	2.2	75.6	11.1	.010	.169							
						C 13.5	.....	2.0	4.6	-2	1.4	78.3	6.2	.004	.128	1,476						
						E 15.2	.....	2.8	8.8	-0	.3	80.9	1.1	.....	.....					
						G 15.9	.....	1.4	1.2	.0	.4	81.1	1.6	.....	.....	1,255	11.8					
207	21.4	11 a. m. to 3.40 p. m.	2.20 to 3.40 p. m.	2.47 to 3.07 p. m.	O	P. ct. 9.0	P. ct. .4	P. ct. 4.4	P. ct. 8.1	P. ct. -3	P. ct. 2.8	P. ct. 75.0	P. ct. 11.6	Gms. .723	Gms. .301			P. ct.	.01	.15	.19	.39
						A 11	10.2	.0	6.8	3.4	-1	78.7	4.3	.....	.003	.089						
						C 12.6	.....	5.2	2.4	-1	.5	79.2	3.0	.001	.054	1,331						
						E 11.9	.....	6.8	1.0	.0	.0	81.2	.1	.....	.....	1,279						
						G 11.4	.....	7.8	1.1	.0	.0	81.1	.1	.....	.....	1,179	17.8					
206	21.4	11.20 a. m. to 4 p. m.	3 to 4 p. m....	3.26 to 3.36 p. m.	O	P. ct. 10.0	P. ct. .1	P. ct. 4.7	P. ct. 8.0	P. ct. .4	P. ct. 1.5	P. ct. 75.3	P. ct. 10.0	Gms. .020	Gms. .064			P. ct.	.03	.14	.17	.37
						A 11	10.0	.0	7.3	3.7	.1	78.1	4.6	.....	.005	.075						
						C 12.5	.....	5.0	2.8	.1	.5	79.1	3.4	.003	.059	1,346						
						E 10.3	.....	8.5	.2	.0	.0	81.0	.2	.....	.....	1,246						
						G 9.5	.....	9.7	.1	.0	.0	80.7	.1	.....	.....	1,152	21.2					
185	22.1	10.40 a. m. to 4.42 p. m.	3 to 4.40 p. m..	3.36 to 3.59 p. m.	H	P. ct. 9.5	P. ct. 9.8	P. ct. 9.8	P. ct. .0	P. ct. .0	P. ct. .0	P. ct. 80.7	P. ct. .0	.....	.....	1,059		P. ct.	.03	.14	.09	.68
						A 10.2	.....	8.0	2.7	.0	.5	78.6	3.2	.....	.....	1,044						
						C 8.4	.....	10.9	1.1	.0	.2	79.4	1.3	.....	.....					
						E 10.1	.....	9.3	.2	.0	.0	80.4	.2	.....	.....	1,204						
						G 7.9	.....	11.8	.0	.0	.0	80.3	.0	.....	.....	1,119	22.8					
						G 8.8	.....	10.7	.0	.0	.0	80.5	.0	.....	.....	1,064	103.0					

TABLE 3.—*Results of combustion tests*—Continued.

PITTSBURGH SCREENINGS—Continued.

Test No.	Coal fired per square foot of grate area per hour.	Duration of test.	Period used for obtaining averages of gas temperatures and pressures.	Period of gas sampling.	Section of furnace where samples were taken.	Average composition of gases, by volume.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature.	Weight of air per pound of combustible.	Excess of air.	Gas pressure, inches of water.			
						CO ₂ .	Unsaturated hydrocarbons.	O ₂ .	CO.	CH ₄ .	H ₂ .	N ₂ .	Total gaseous combustible.						In ash pit, above atmospheric.	Over fuel bed, below atmospheric.	At rear of chamber, below atmospheric.	In uptake, below atmospheric.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Lbs.					P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Gms.	Gms.	° C.	Lbs.	P. ct.	0.30	0.13	0.25	1.26
189	39.2	12 m. to 3.40 p.m.	2.40 to 3.40 p.m.	3 to 3.21 p.m.	A B C D E F G H	10.4	3.6	8.4	0.4	2.5	74.7	11.2	0.024	0.113	1,610	14.1	25.7	0.30	0.13	0.25	1.26	
						10.1	4.1	4.1	0.2	1.1	78.5	11.2	0.014	0.160	1,427	14.1	25.7	0.30	0.13	0.25	1.26	
						13.2	3.9	2.8	0.0	1.1	79.0	3.9	0.014	0.160	1,427	14.1	25.7	0.30	0.13	0.25	1.26	
						13.8	4.3	3.6	0.0	1.1	81.2	3.9	0.014	0.160	1,427	14.1	25.7	0.30	0.13	0.25	1.26	
187	35.6	11 a. m. to 4 p.m.	2 to 4 p.m.	2.52 to 3.12 p.m.	A B C D E F G H	7.3	0.9	1.3	16.4	8	7.6	65.8	25.7	2.232	272	1,283	14.5	29.0	0.30	0.19	0.27	1.05
						11.6	0	2.9	6.4	4	3.3	75.4	10.1	0.006	0.069	1,530	14.5	29.0	0.30	0.19	0.27	1.05
						13.5	0	3.2	3.1	0	1.5	78.7	4.6	0.006	0.069	1,530	14.5	29.0	0.30	0.19	0.27	1.05
						13.6	4.9	4.4	0	0	81.1	4.4	0.006	0.069	1,530	14.5	29.0	0.30	0.19	0.27	1.05	
193	42.0	11 a.m. to 3.40 p.m.	2.40 to 3.40 p.m.	2.57 to 3.17 p.m.	A B C D E F G H	10.1	5.7	12.7	1	2.2	72.6	15.0	0.025	0.089	1,243	14.5	29.0	0.48	0.24	0.34	1.04	
						13.2	4.0	7.8	2.6	1.1	79.5	3.9	0.002	0.102	1,566	14.5	29.0	0.48	0.24	0.34	1.04	
						13.3	4.8	3.0	0	0	81.0	3.2	0.002	0.102	1,566	14.5	29.0	0.48	0.24	0.34	1.04	
						13.8	4.3	2.0	0	0	81.0	3.2	0.002	0.102	1,566	14.5	29.0	0.48	0.24	0.34	1.04	
205	35.2	11.20 a. m. to 4.20 p.m.	3.07 to 4.20 p.m.	3.33 to 3.55 p.m.	A B C D E F G H	8.6	3	1.8	15.3	2	3.4	70.4	19.2	0.033	0.171	1,252	14.5	29.5	0.21	0.25	0.28	0.72
						10.3	0	2.1	10.0	3	3.2	74.1	13.5	0.027	0.272	1,495	14.5	29.5	0.21	0.25	0.28	0.72
						12.8	0	1.7	7.5	1	9.9	77.0	8.5	0.008	0.050	1,495	14.5	29.5	0.21	0.25	0.28	0.72
						12.1	6.2	2.8	0	0	80.7	1.0	0.008	0.050	1,495	14.5	29.5	0.21	0.25	0.28	0.72	

194	44.2	11.20 a. m. to 3.40 p. m.	2.40 to 3.40 p. m.	3.01 to 3.21 p. m.	0 11 A 10.9 C 9.7 E 9.1 G 10.6	9.3 6.6 7.0 9.5 10.3 8.7	4.3 2.3 4 0 0 0	9.5 2.3 4 0 0 0	.1 0 0 0 0 0	2.1 80.0 80.7 80.8 80.6 80.7	74.7 2.7 0 0 0 0	11.7 0.03 0.01 0.01 0.01 0.01	.052 .071 0 0 0 0	.....	.....	.25 .46 .56 1.23
204	37.9	11.20 a. m. to 3.40 p. m.	2.40 to 3.40 p. m.	2.55 to 4.04 p. m.	0 11 A 8.6 C 12.5 E 10.1 G 9.8	8.6 5.3 7.8 8.5 9.1 9.4	.1 9.3 7.8 8.5 9.1 9.4	9.3 2.5 2.5 0 0 0	.2 1 1 0 0 0	1.6 74.9 78.9 79.4 81.0 80.8	11.3 3.5 3.0 0 0 0	.024 .073 .015 .003 0 0	.073 .145 .033 .033 0 0	.....	.....	.21 .18 .25 .78
199	47.1	11 a. m. to 3.40 p. m.	2 to 3.40 p. m.	2.39 to 3 p. m.	0 11 A 11.1 C 12.5 E 15.7 G 15.8	6.2 3.4 4.6 3.3 2.2 2.4	.1 13.4 3.3 3.3 1.5 2.4	13.4 3.3 3.3 1.5 2.2 2.4	1.0 1 1 0 0 0	9.0 66.9 78.9 77.4 80.9 81.4	66.9 23.5 5.4 8.4 1.8 7	.056 .173 .003 .003 0 0	.173 .114 .061 .061 0 0	.....	.....	.49 .20 .30 .74
192	45.3	11 a. m. to 3.20 p. m.	2.20 to 3.20 p. m.	2.42 to 3.02 p. m.	0 11 A 10.4 C 13.7 E 14.1 G 13.6	6.4 5.3 3.9 4.4 4.1 4.7	.3 4.8 4.4 1 2 1	4.8 4.4 1 2 1	.2 1 1 0 0 0	3.4 69.8 78.2 81.1 81.4 81.6	69.8 21.0 6.1 5.6 1.1 3	.031 .057 .005 .004 0 0	.057 .111 .111 .091 0 0	.....	.....	.44 .36 .43 .90
200	50.5	11 a. m. to 3.40 p. m.	2.40 to 4 p. m.	2.58 to 3.18 p. m.	0 11 A 14.5 C 11.4 E 11.4 G 10.9	12.8 9.8 4.6 7.4 7.5 8.1	.3 7.7 4.6 7.4 7.5 8.1	7.7 4.6 7.4 7.5 8.1 8.1	1.2 3.6 1.0 1.0 0 0	3.6 74.8 81.4 76.3 81.0 81.1	74.8 9.3 1.1 4.6 0 0	.079 .052 .003 .002 0 0	.052 .111 .035 .031 0 0	.....	.....	.52 .40 .54 1.06
201	60.0	11.20 a. m. to 4.20 p. m.	3 to 4.20 p. m.	3.36 to 3.56 p. m.	0 11 A 12.3 C 13.4 E 13.9 G 13.4	9.3 3.8 2.5 2.5 2.7 5.3	.1 8.8 3.1 3.9 2 5.3	8.8 3.1 3.9 2 5.3 5.3	.4 1 1 0 0 0	3.1 74.5 76.6 81.2 81.3 81.3	74.5 12.4 4.3 5.2 2 0	.032 .112 .003 .002 0 0	.112 .104 .133 .094 0 0	.....	.....	.45 .28 .34 .76
202	57.3	11.20 a. m. to 4.30 p. m.	3.40 to 4.30 p. m.	3.57 to 4.18 p. m.	0 11 A 10.1 C 12.3 E 12.4 G 12.6	7.8 6.1 4.0 5.9 6.4 6.3	.1 9.1 7.1 2.1 0 0	9.1 7.1 2.1 0 0 0	.4 2 1 0 0 0	3.2 73.3 76.7 81.3 81.2 81.1	73.3 12.8 9.2 2.9 0 0	.008 .056 .003 .002 0 0	.056 .133 .133 .045 0 0	.....	.....	.59 .33 .35 .69

DISCUSSION OF COMBUSTION PROCESS IN COMBUSTION SPACE.

The combustion process in the combustion space above and beyond the fuel bed is well illustrated in figure 13, which gives the percentage of the main constituents of the furnace gases at various sections of the long combustion chamber. The figure represents the actual conditions of test 187. The ordinates are the percentages of gases by volume; the abscissa has two scales—namely, volume of combustion

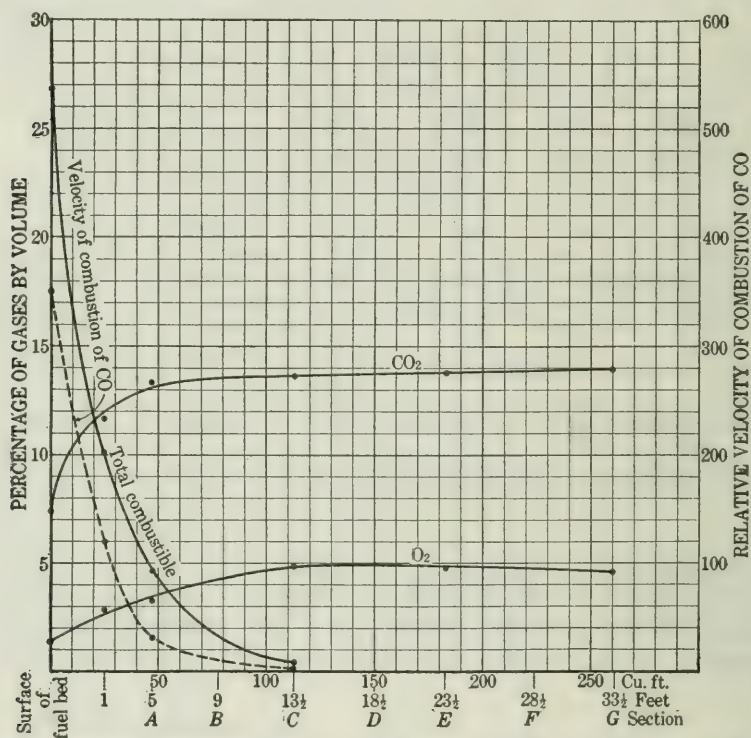


FIGURE 13.—Progress of composition of furnace gases at various distances above the fuel bed. Test 187, Pittsburgh screenings; rate of combustion, 35.6; sampling period, 20 minutes.

space in cubic feet and the average length of gas travel from the surface of the fuel bed. The points representing the composition of gases at the surface of the fuel bed are the averages of seven samples; at 1 foot from the surface of fuel bed, eight samples; at A, six samples; and at C, E, and G, nine samples. All of these 48 gas samples were taken simultaneously over a period of 20 minutes. The rate of combustion was 35.6 pounds of coal per square foot of grate area. The coal used was Pittsburgh screenings. The curve labeled "total combustible" represents the sum of combustible gases as given in Table 3, column 14.

The curves show that the gases leaving the fuel bed contain over 25 per cent of combustible gases, about one per cent of O_2 , and 7 per cent of CO_2 . Before these gases reached section A, enough air was added to make the total air supply exceed the amount theoretically needed by 19 per cent. Most of this air was added through the tuyères very near to the surface of the fuel bed, and in a way that facilitated its mixing with the combustible gases rising from the fuel bed. The mixing is illustrated in figure 7. The progress of combustion is indicated by the drop of the total combustible curve and the rise of the CO_2 curve. The change in the composition of the gases indicated by these two curves show that the combustion is most rapid within a foot from the surface of the fuel bed; as the gases pass farther away from the fuel bed the rapidity of combustion decreases. At a distance of $13\frac{1}{2}$ feet from the grate there is very little combustible gas left, showing that combustion is practically complete.

The length or the volume of the combustion space required for practically complete combustion seems to depend chiefly on the percentage of excess air, the rate of combustion, and the kind of coal. It is mainly these three factors that have been investigated in the series of tests reported in this bulletin.

The effect of these three factors on the length or volume of the combustion space required for practically complete combustion is shown in a general way in figures 14 to 18, inclusive. These figures are compiled from the 100 tests shown in Table 3. The curves were plotted with the percentage of gaseous combustible in furnace gases as ordinates and the length and volume of combustion space as abscissas. In these figures and those that follow the length of the combustion space in feet is shown at the bottom of the figure, as are the corresponding volumes in cubic feet. Near the fuel bed the volume is much larger per foot of length of gas travel than it is in the uniform cross section of the combustion chamber.

The tests are grouped according to the kind of coal, and according to the rate of combustion. Within each group having the same rate of combustion, individual tests were made with different percentages of excess air. To prevent the diagrams from being crowded, only the curves giving the total combustible gases were plotted, those showing CO_2 and O_2 being omitted, and when more than one test was run with nearly the same excess of air, a curve giving the average of these tests has been plotted instead of each test being plotted separately. The general shape of the curves is the same as that of the combustible curve shown in figure 13. The rapidity of combustion is highest near the fuel bed, and decreases as the gases flow farther away.

Comparison of the different curves showing the same rate of combustion indicate that when the air excess is large the proportion of combustible gases is less at any given cross section of the furnace,

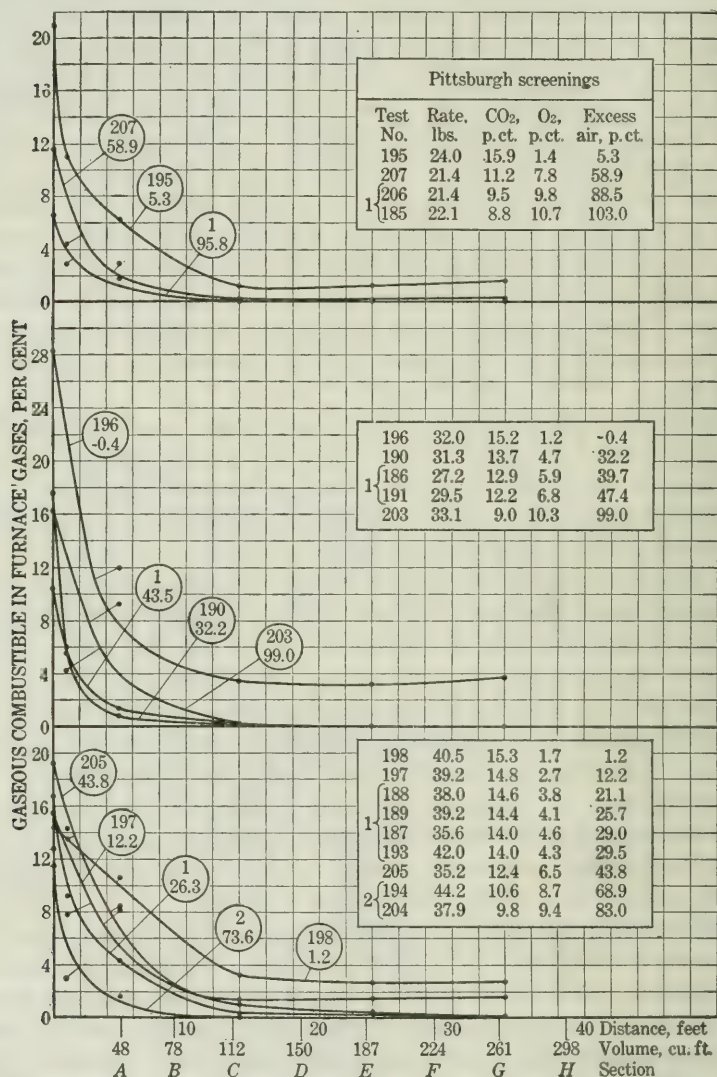


FIGURE 14.—Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 20, 30, and 40 pounds.

and the combustion is practically complete in a smaller combustion space than when the excess of air is small. Some of the curves and individual points fall out of place. The three main causes of these irregularities are (a) lack of constancy in mixing of the com-

bustible rising from the fuel bed with the air supplied over the fire; (b) the difficulty of obtaining a fair average sample; and (c) the fact that the rate of combustion during the short sampling period may not have been the same as the average rate of the whole test. These three factors are discussed below.

Under normal conditions the air supplied over the fuel bed is introduced through the tuyères as a large number of small jets.

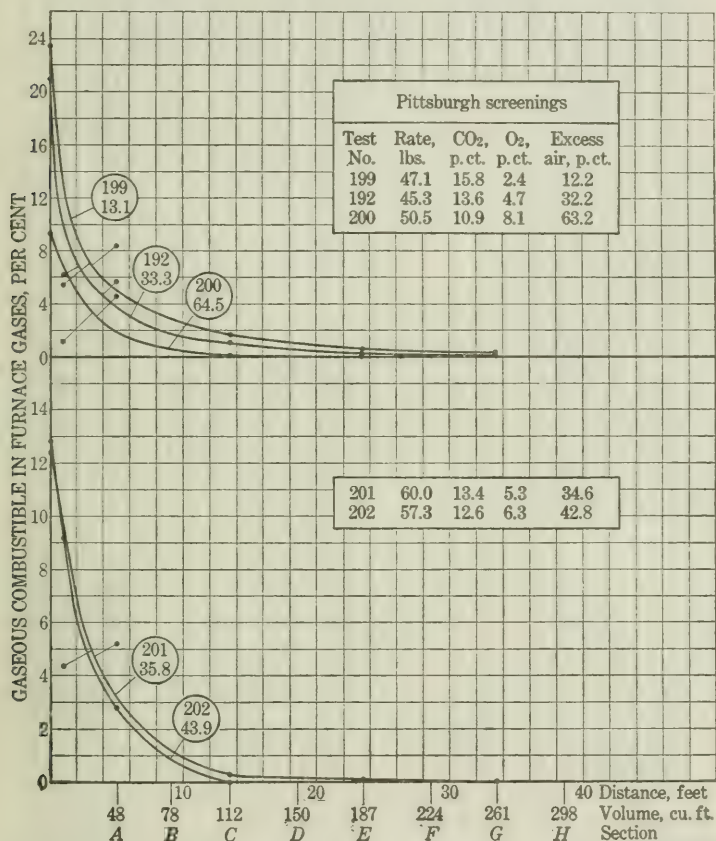


FIGURE 15.—Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 50 and 60 pounds.

This method of introducing the air produces relatively good mixing. When, however, all the air can not be supplied through the tuyères and part of it must be introduced either through the firing door or through the coal magazines, the air thus admitted enters in large streams and does not mix readily with the combustibles; the gases tend to remain stratified and in spite of the large excess of air the combustion does not proceed much faster than when the air is introduced only through the tuyères.

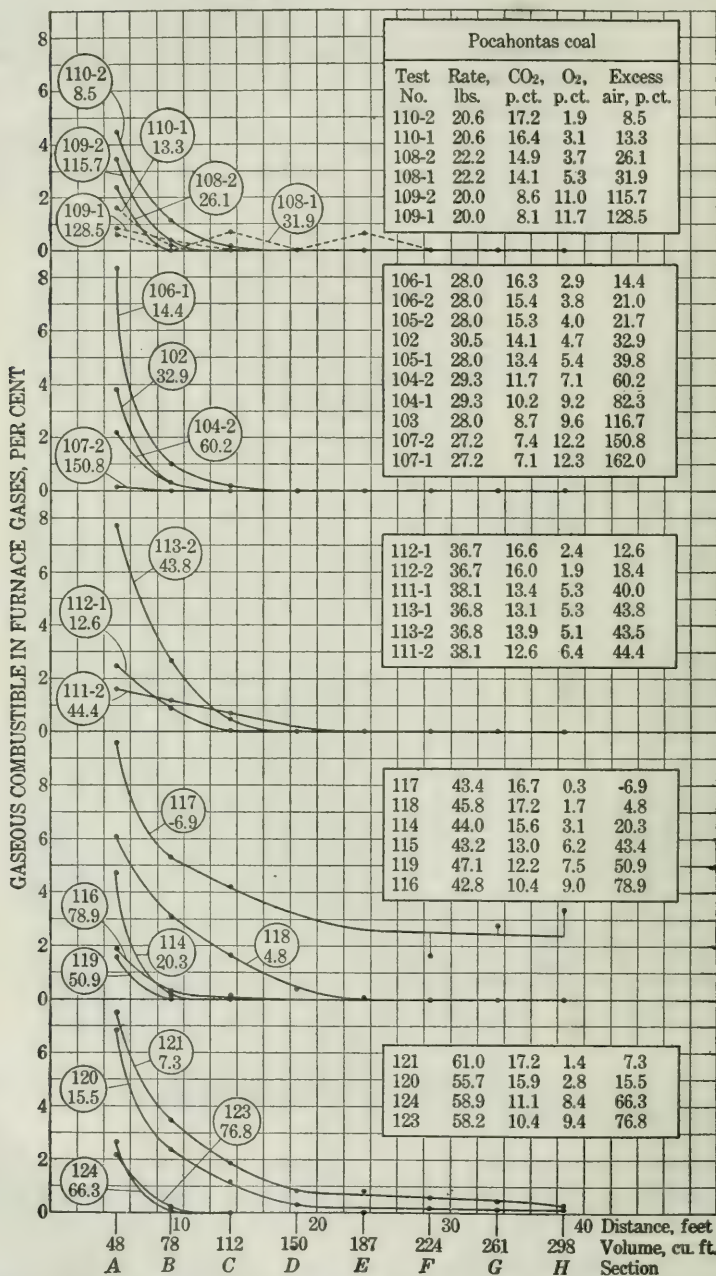


FIGURE 16.—Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pocahontas coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.

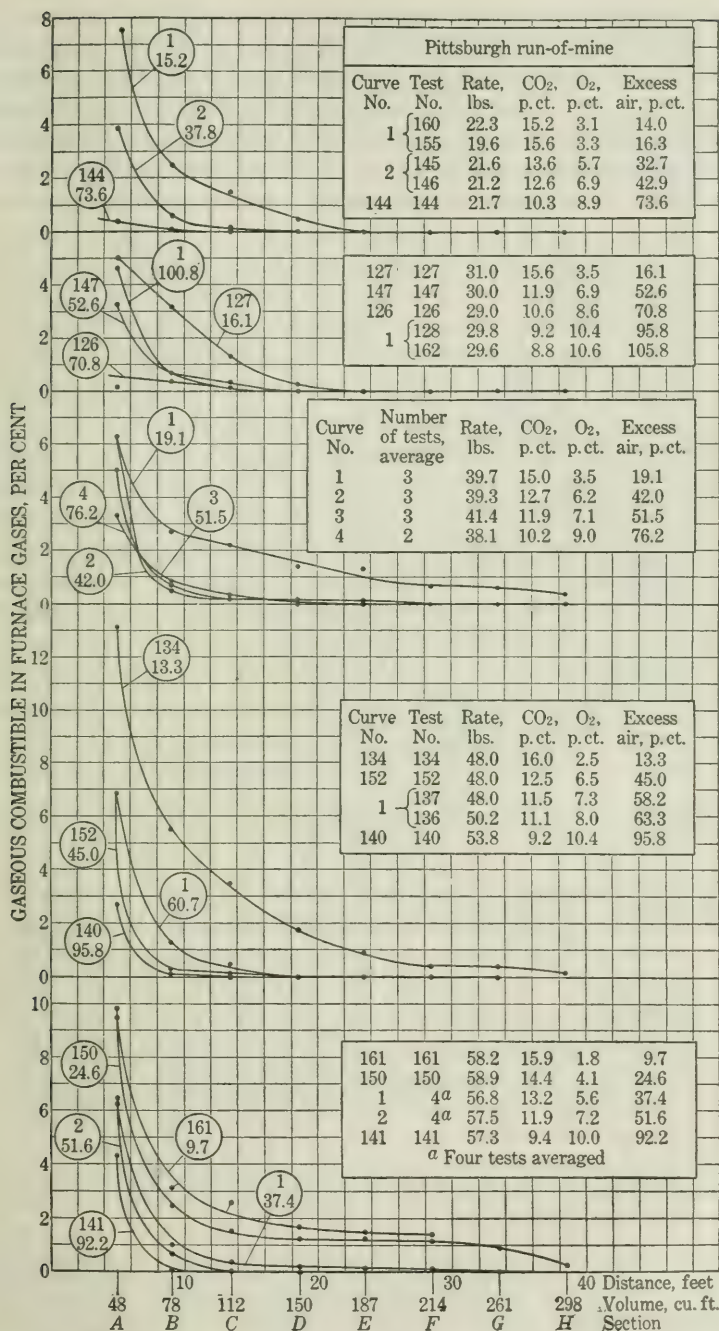


FIGURE 17.—Relation between the percentage of gaseous combustible in furnace gases and the length and volume of combustion space, as shown by tests made with Pittsburgh run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50 and 60 pounds.

Obtaining a fair average sample of furnace gases from the space over the fuel bed, where the gases are greatly stratified, is particularly difficult. This difficulty can be better appreciated by examining figure 7 (p. 17) which shows the streams of gases and the position of gas samplers over the fuel bed. The upper holes of the two side rows of gas samplers are in the path of the air coming in through the tuyères. As a result of this position the average of the gas samples

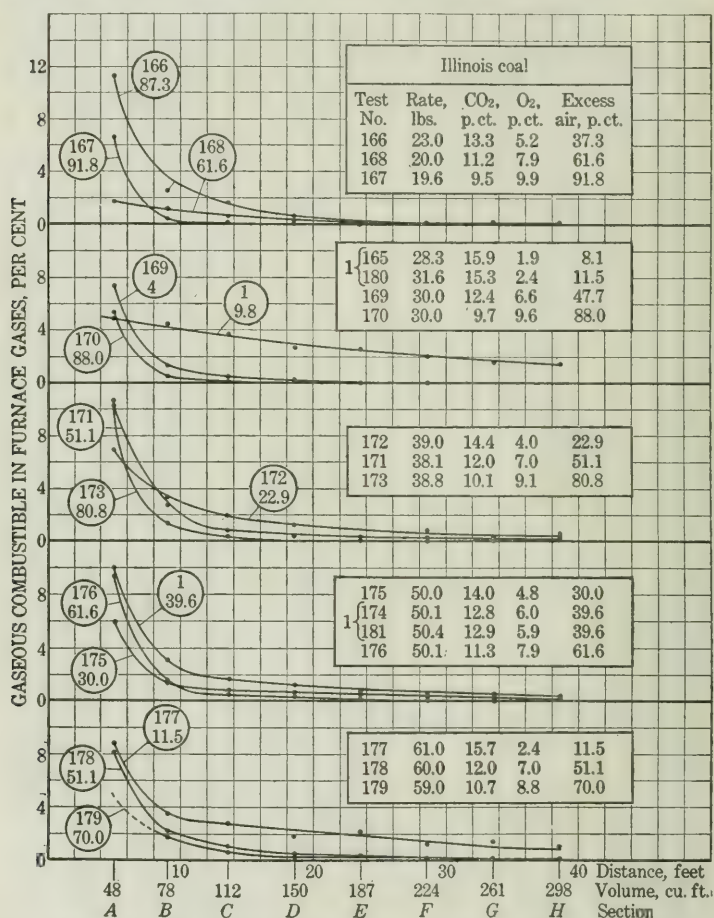


FIGURE 18.—Relation between the percentage of gaseous combustibles in furnace gases and the length and volume of combustion space, as shown by tests made with Illinois coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.

collected 1 foot from the surface of the fuel bed is too high in free oxygen and too low in total combustible content. This statement is confirmed by the results shown in figures 14 to 18, inclusive; the points giving the percentage of combustible 1 foot above the fuel bed appear to be all too low, in fact some of them are considerably lower than the points representing samples taken at section A. In drawing the curves the points representing samples taken 1 foot

from the fuel bed and those for samples at section A have been given equal weight and the line passes about midway between the two points. Perhaps the curves should have been passed nearer to the points representing samples from section A.

Although the coal was fed to the magazines at a uniform rate throughout the entire length of a test, the rate of combustion during the sampling period may have been either lower or higher than that shown by the average for the test. Variation in the rate of combustion is apt to occur even with the most careful control of the fire. All the four coals tested tended to cake and to accumulate on the portion of the grate near the magazines, while farther away wide cracks formed in the fuel bed and bare spots on the grate. Consequently the caked coal had to be frequently pulled down over the cracks and bare spots by the furnace attendant. Under such conditions it is possible for the instantaneous rate of combustion to vary 25 per cent below or above the average rate for the entire test.

Comparison of the different groups of curves in figures 14 to 18, inclusive, show that with higher rates of firing more combustion space is needed to obtain nearly complete combustion than when the rate of firing is low. These figures show this relation only in a general way, because the tests with different rates of firing were not run with absolutely the same excess of air. The air supply was the most difficult factor to control. In plotting figures 28 to 30 (pages 73 to 75), some points were interpolated in order to reduce the effect of variation in air supply.

UNDEVELOPED HEAT OF FURNACE GASES ALONG THEIR PATH OF TRAVEL.

The curves of figures 14 to 18, inclusive, are somewhat misleading. The low percentage of combustible in the furnace gases when the excess of air is large is not entirely a result of improved combustion, but to some extent is due to the dilution of the gases with air. It is evident that with a large excess of air, the percentage of combustible gases is less, even if there be no improvement in the combustion. Therefore, when the air supply is varied the percentage of combustible gases does not reliably indicate the completeness of combustion. To eliminate the effect of this dilution with air, the content of gaseous combustible was expressed as a percentage of the calorific value of the coal; that is, the amount of unburned combustible gases represents so many per cent of the total heat value of the coal. In making this change each constituent of the combustible gases was given its heat value. The unsaturated hydrocarbons were considered as C_2H_4 . The following is the general formula used in the calculation:

$$H = \left(\frac{CO \times 12 \times 10,100 + CH_4 \times 16 \times 23,500 + H_2 \times 62,000 + C_2H_4 \times 28 \times 21,300}{12(CO_2 + CO + CH_4 + 2C_2H_4)} \times \text{heat of moisture and ash free coal} \right) \times \text{per cent of carbon in moisture and ash free coal.}$$

In the formula H is the undeveloped heat of the combustible gases in the furnace, expressed as a percentage of the total heat value (B. t. u. per pound) in the coal, and CO_2 , CO , CH_4 , H_2 , and C_2H_4 are the percentages of the respective gases as determined by volumetric analysis. With Pittsburgh coal this formula reduces to the following simpler form:

$$H = \frac{58\text{CO} + 179\text{CH}_4 + 59\text{H}_2 + 285\text{C}_2\text{H}_4}{\text{CO}_2 + \text{CO} + \text{CH}_4 + 2\text{C}_2\text{H}_4}$$

The heat values thus obtained are only approximate, because the equation does not take into account the carbon rising from the fuel bed in the form of soot and tar, but are within a few per cent of the correct value. The maximum error is probably not over 5 per cent. To get the correct value for the undeveloped heat, both the numerator and the denominator of the equation should contain the soot and tar terms. To incorporate these two terms in the equation would be difficult, because the exact composition of the tar and the soot and their heating values are not known. Furthermore, both the gases and the tar and soot would have to be reduced to a common basis of percentage by weight, and it is difficult to obtain the soot and tar sample accurately. As the equation stands H is too high and approaches the correct value as the tar and soot disappear from the furnace gases.

The values of H determined by the equation were plotted as ordinates with the length and volume of combustion space as abscissas. The results so plotted are given in figures 19 to 23, inclusive, the tests being arranged in groups similar to those in figures 14 to 18. Each group contains the results of tests with the same coal at the same rate of combustion, but different amounts of excess air. To avoid crowding in the illustrations, when there is more than one test with the same excess of air, the averages of these tests are plotted instead of each test being plotted separately. The test number and the percentage of excess of air are shown within the small circles attached to each curve.

The curves are similar in shape to those in figures 14 to 18, which are plotted on the percentage of combustible gas as ordinates, with the exception that the rise on the left is steeper. As mentioned in previous paragraphs the points at the left are too high on account of the large amount of tar and soot carried by the gases near the surface of the fuel bed.

It is interesting to note that at the surface of the fuel bed the combustible gases represent 35 to 65 per cent of the total heat value of the coal. This means that under ordinary operation of the side-feed furnace about one half of the total heat in the coal is developed in the fuel bed, the other half being developed in the combustion space. Among other factors, it depends upon the size of the com-

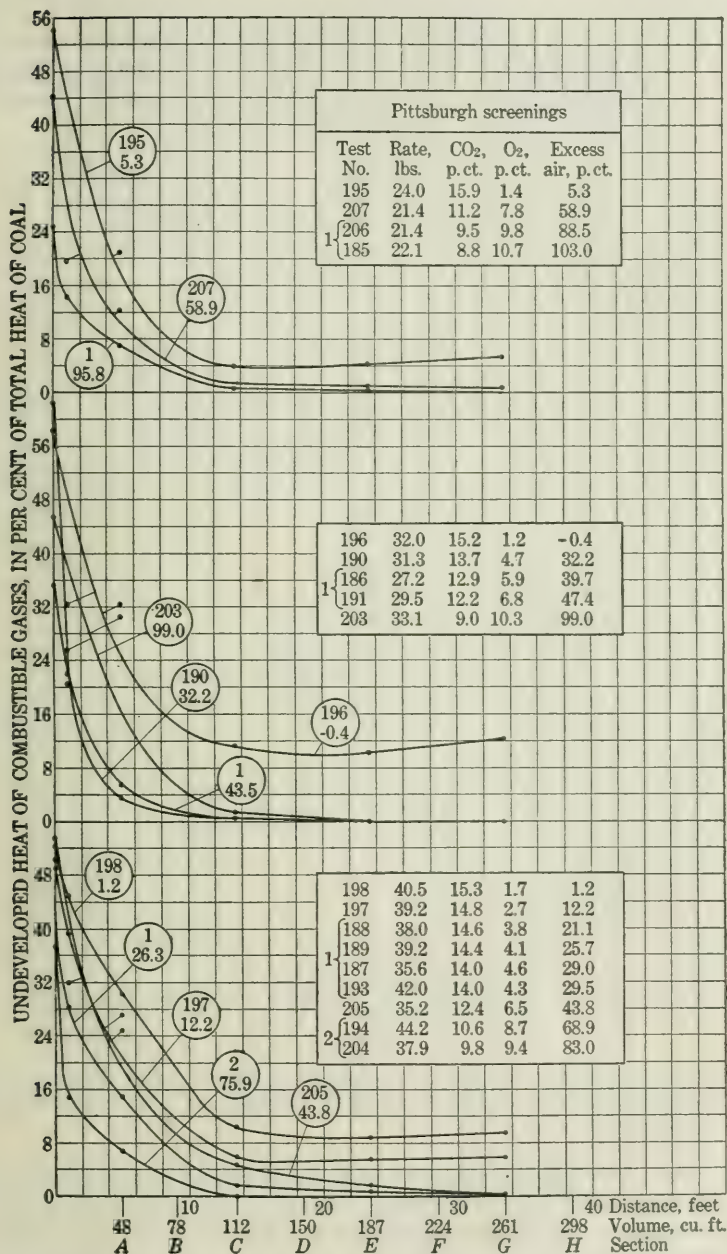


FIGURE 19.—Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 20, 30, and 40 pounds.

bustion space how much of the 50 per cent of heat left in the combustible rising from the fuel bed is developed. The curves of figures 19 to 23 show this relation of completeness of combustion to the length and volume of the combustion space, and also the effect of the excess of air and the rate of firing on the completeness of combustion at the various sections of the combustion space.

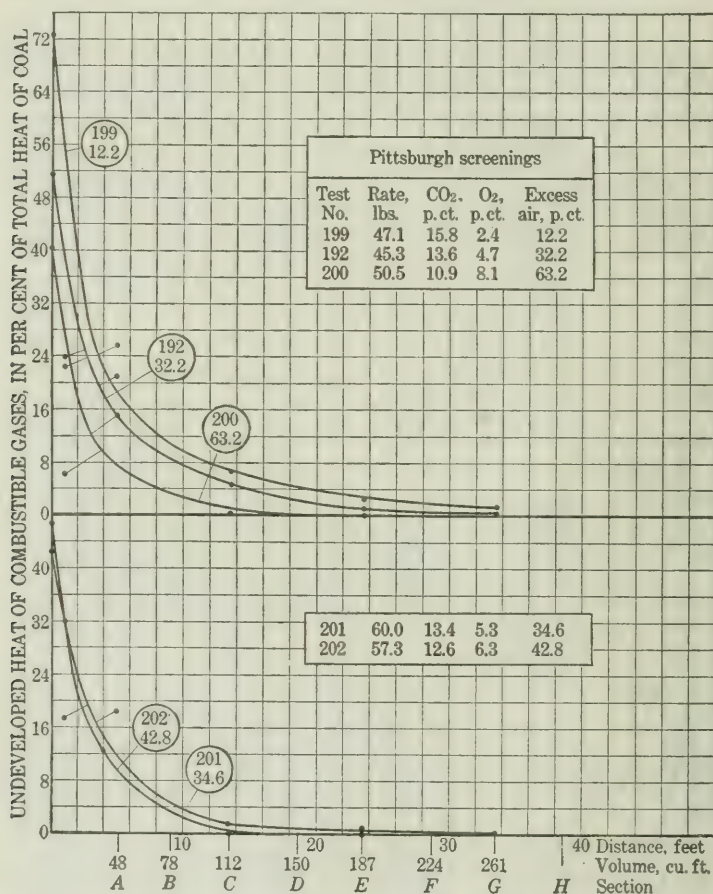


FIGURE 20.—Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh screenings at rates of combustion of approximately 50 and 60 pounds.

In general, the curves of figures 19 to 23 show that when the excess of air is increased the combustion requires less space to become nearly complete. A few tests do not seem to conform to this principle, and their curves fall out of place. There may be several reasons for this discrepancy, the three principal ones being those already stated on pages 56 and 57 in connection with figures 14 to 18.

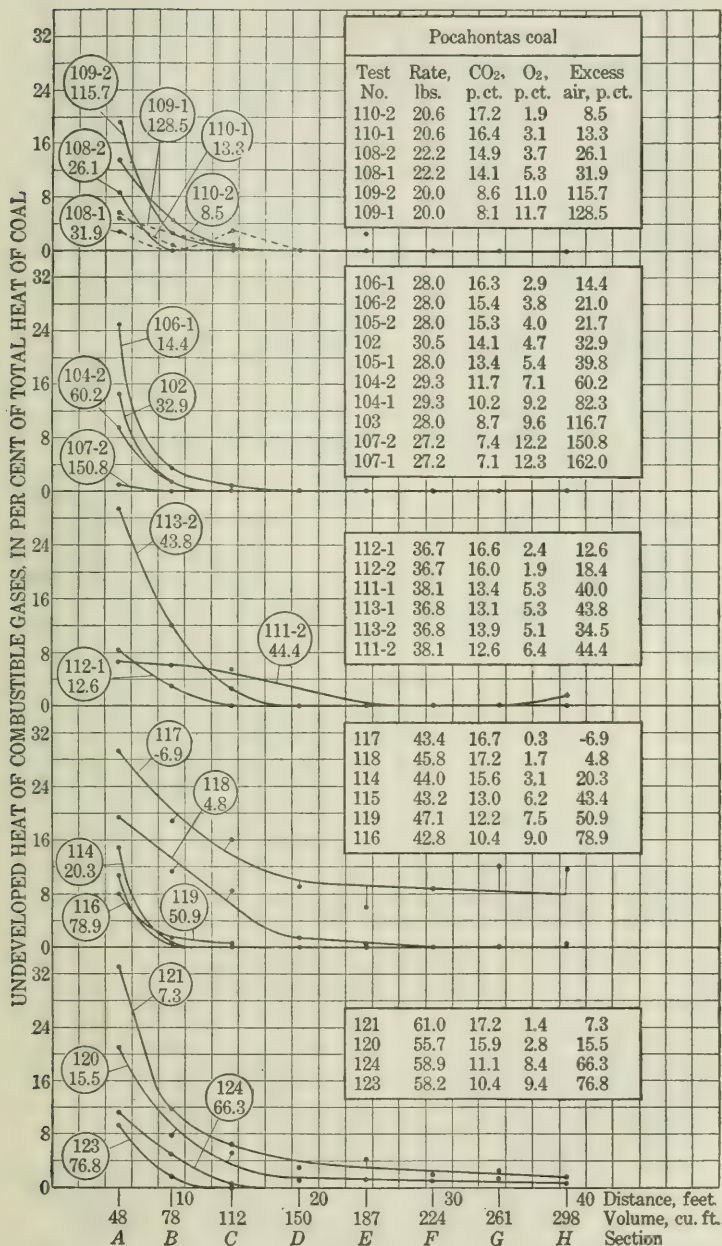


FIGURE 21.—Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pocahontas run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.

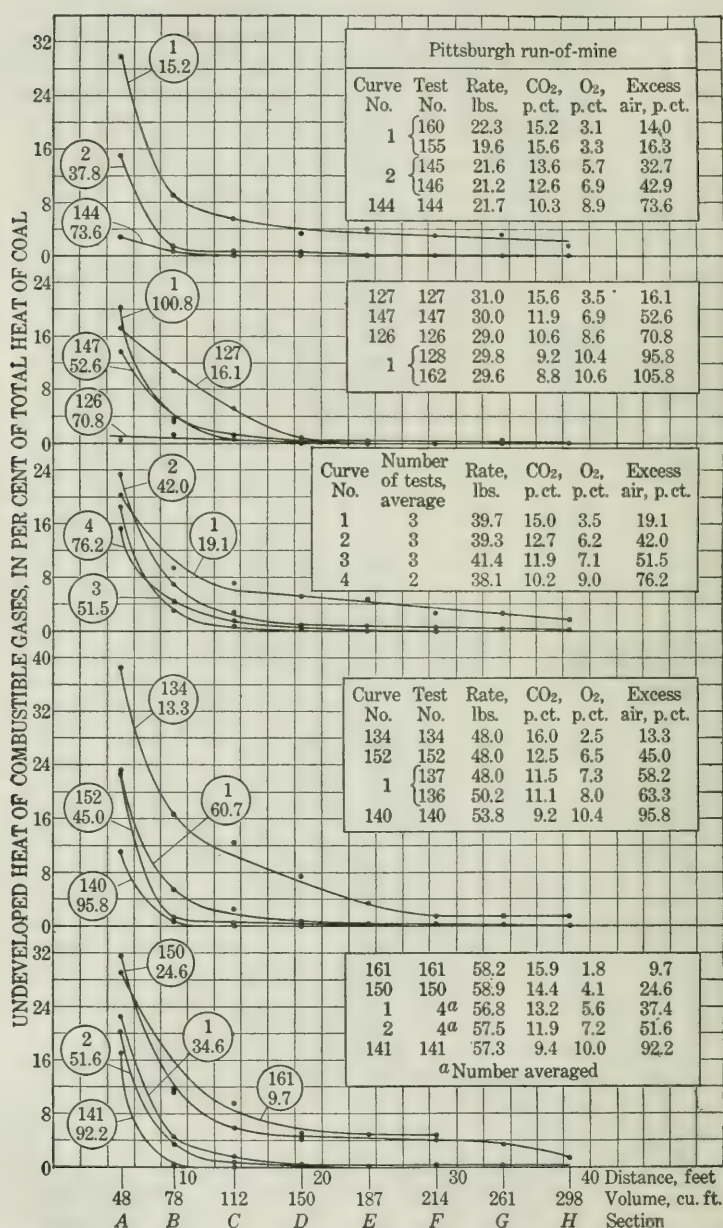


FIGURE 22.—Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Pittsburgh run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.

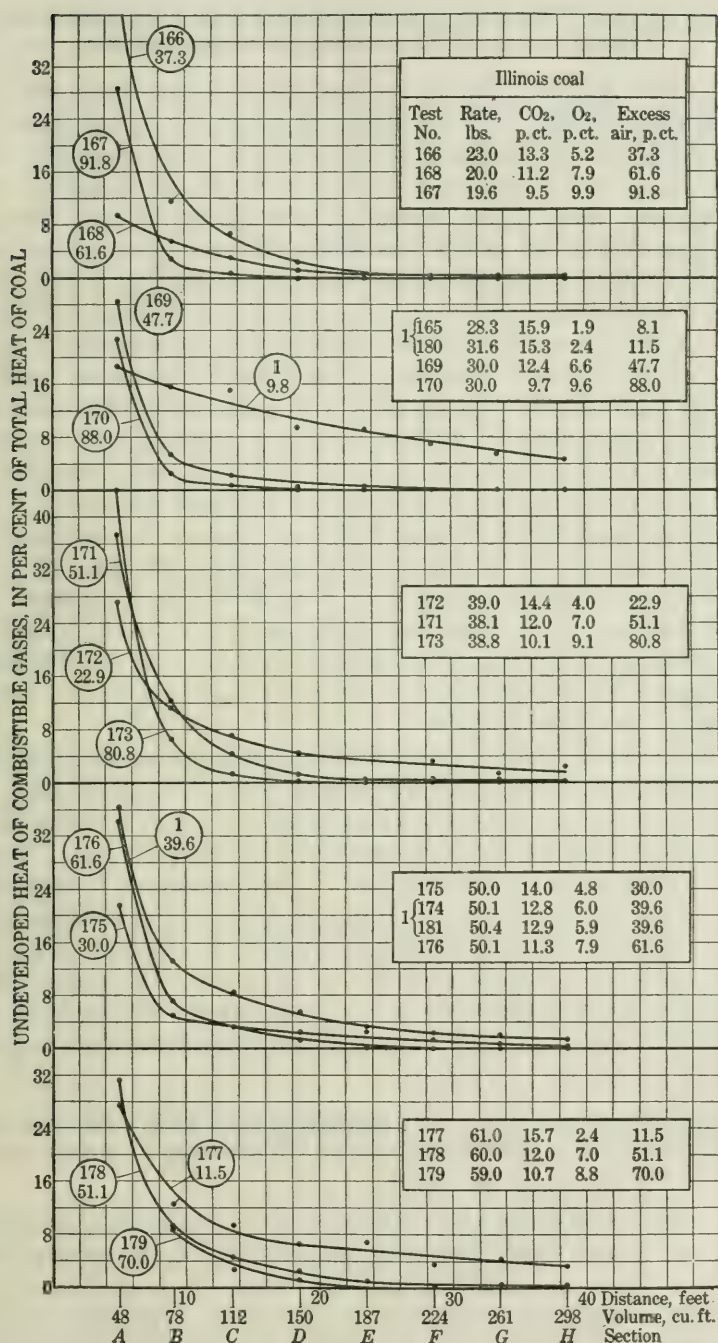


FIGURE 23.—Relation between the completeness of combustion and the length and volume of combustion space, as shown by tests made with Illinois run-of-mine coal at rates of combustion of approximately 20, 30, 40, 50, and 60 pounds.

EFFECT OF THE PERCENTAGE OF EXCESS AIR AND THE RATE OF FIRING ON COMPLETENESS OF COMBUSTION.

The effect of the percentage of excess air on the completeness of combustion is shown better in figures 24 to 27. In these figures the undeveloped heat represented by the combustible gases at each cross section is plotted as ordinates with the percentage of excess of air as abscissas. Each figure represents one coal, and each group of points one section of the combustion chamber. The rate of combustion is indicated by the size or shape of the plotting points. The curves thus obtained show that at any of the cross sections beyond section A the percentage of the undeveloped heat increases as the excess of air becomes smaller. This relation is rather definite, although there are not enough tests with each rate of combustion to give a smooth individual curve. However, the points representing tests with rates of combustion of 40, 50, and 60 pounds invariably fall higher than the points representing rates of 20 and 30 pounds. Thus by dividing each series of tests into two groups, one including all tests with rates of 40, 50, and 60, and the other with rates of 20 and 30 pounds, a sufficient number of tests is obtained to draw two smooth curves, one representing approximately a rate of 50 and the other a rate of 25 pounds. In the series of tests with the Pittsburgh screenings even this grouping does not give enough points for the drawing of two reliable curves.

From the curves of figures 24 to 27, four sets of curves were obtained, showing the completeness of combustion along the path of gases, for the two average rates of firing and the four constant excesses of air. Figure 28 shows a set of these curves representing the series of tests with the Pittsburgh run-of-mine coal. The points used for obtaining these curves are the intersection points of the vertical lines representing constant amounts of excess air with the curves of the two average rates of combustion in figures 24 to 27. The curves themselves have little significance, hence only one set is presented, and were prepared only for compiling the more significant curves shown in figures 29 and 30.

SIZE OF COMBUSTION SPACE REQUIRED FOR ANY DESIRED COMPLETENESS OF COMBUSTION, RATE OF FIRING, AND EXCESS OF AIR.

The relation between the required size of combustion space and any given rate of firing, excess of air and the completeness of combustion is given in figures 29 and 30. Each of these figures gives this relation for two of the four coals tested. The curves to the left of the heavy vertical line dividing the figure into two equal parts represent Illinois coal and those on the right, Pocahontas coal. Each half of the figure shows seven groups of curves, each group representing one degree of completeness of combustion, and each

curve in any one group one percentage of excess of air. In reality each group is a complete figure in itself, having for ordinates rates

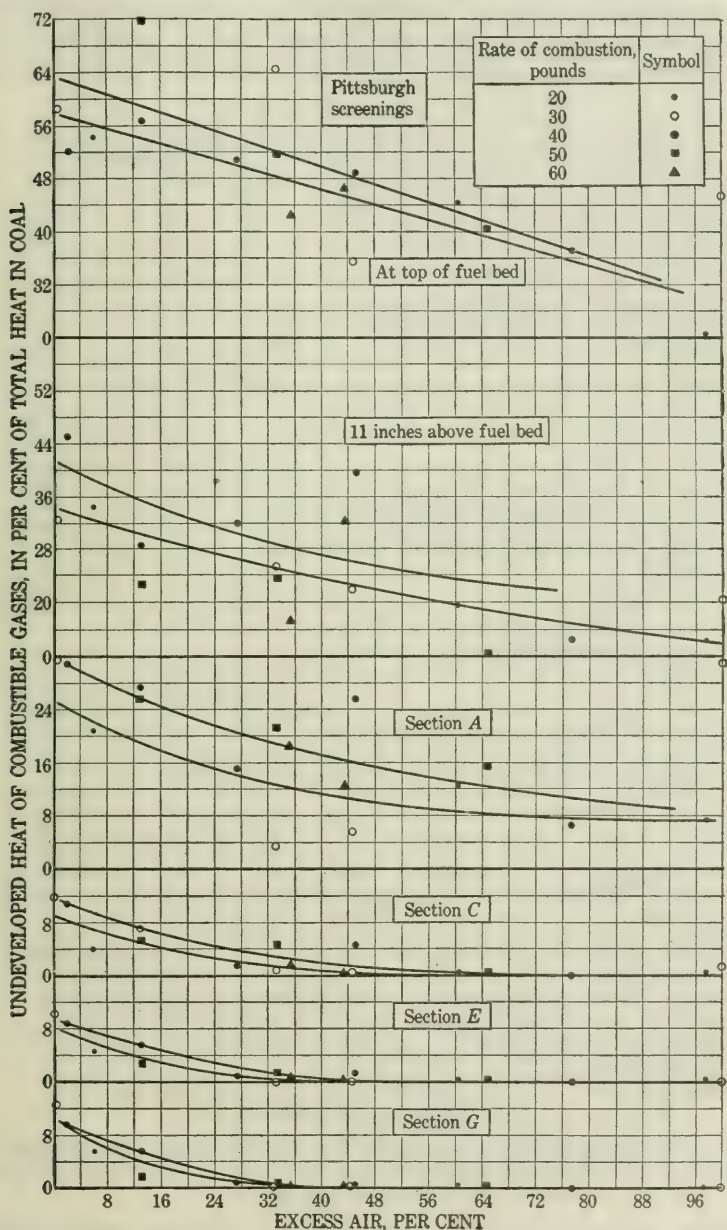


FIGURE 24.—Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pittsburgh screenings. The different rates of combustion are indicated by the size and shape of the points.

of firing ranging from 20 to 60 pounds, and for abscissa the size of combustion space, the latter being given in four scales at the foot

of the figure. Reading from top to bottom, the first scale gives the combustion space in cubic feet; the second scale gives the ratio of the combustion space to the area of grate, or the number of cubic feet of combustion space to each square foot of grate area; the third gives the average length of the path of gas travel; and the fourth

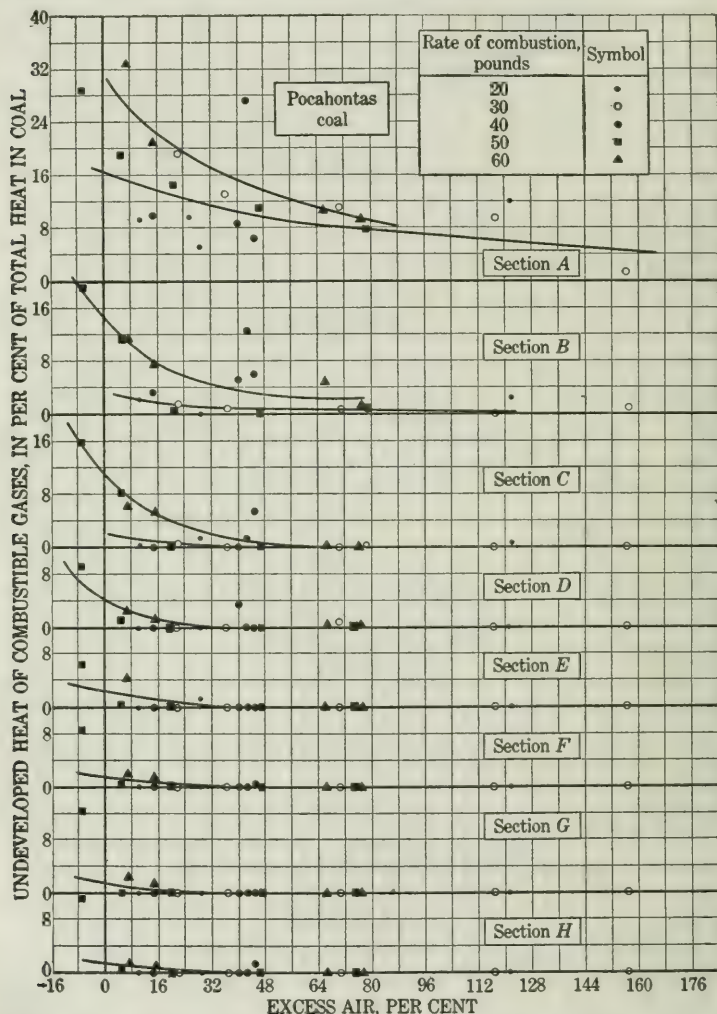


FIGURE 25.—Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pocahontas coal. The different rates of combustion are indicated by the size and shape of the points.

gives the sections at which gas samples in the long combustion chamber were collected.

The curves are drawn as a straight line for the reason that only two points were determined for each curve, the two points being obtained by averaging and partly by interpolation. The curves

are approximate within perhaps 10 to 20 per cent. If it were possible to determine more than two points accurately the curve would very

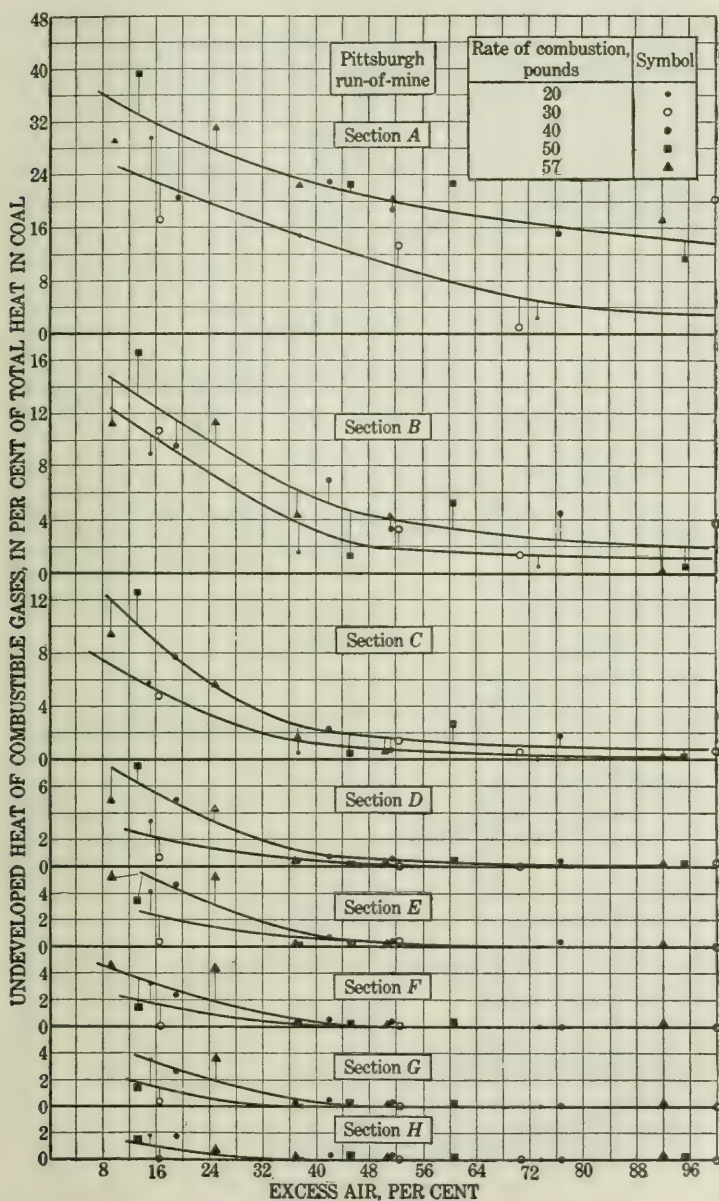


FIGURE 26.—Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Pittsburgh run-of-mine coal. Different rates of combustion are indicated by differently shaped points.

likely approximate the shape of the letter S, similar to that shown by the dotted curves in the middle of figure 29. It is believed,

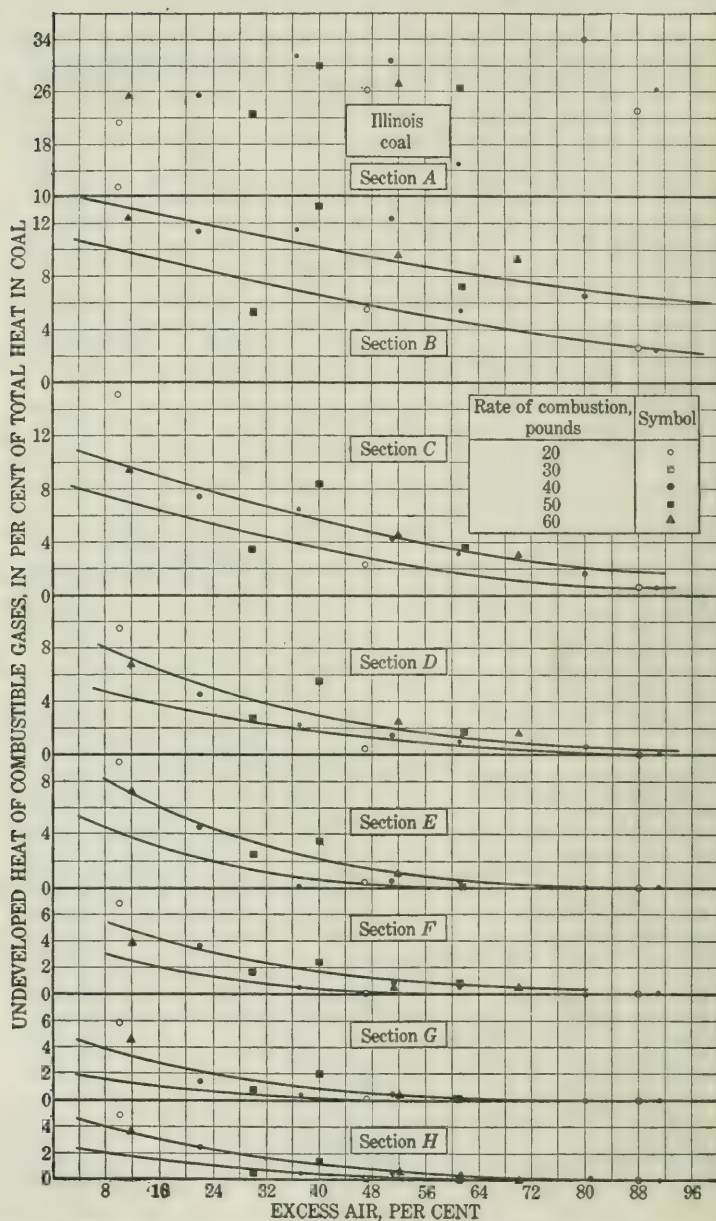


FIGURE 27.—Effect of the percentage of excess air on the completeness of combustion at various cross sections of the long combustion chamber, as shown by tests made with Illinois coal. Different rates of combustion are indicated by differently shaped points.

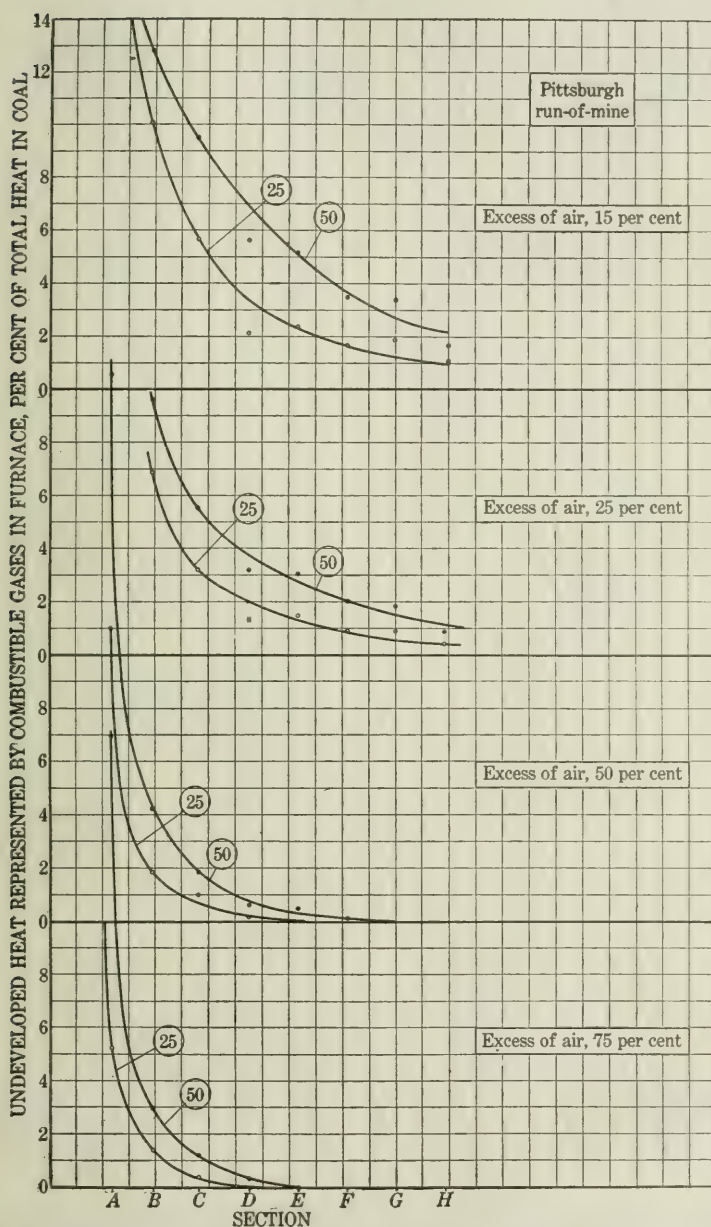


FIGURE 28.—Completeness of combustion along the path of the gases with four percentages of excess of air and average rates of combustion of 25 and 50 pounds, as shown by tests made with Pittsburgh run-of-mine coal.

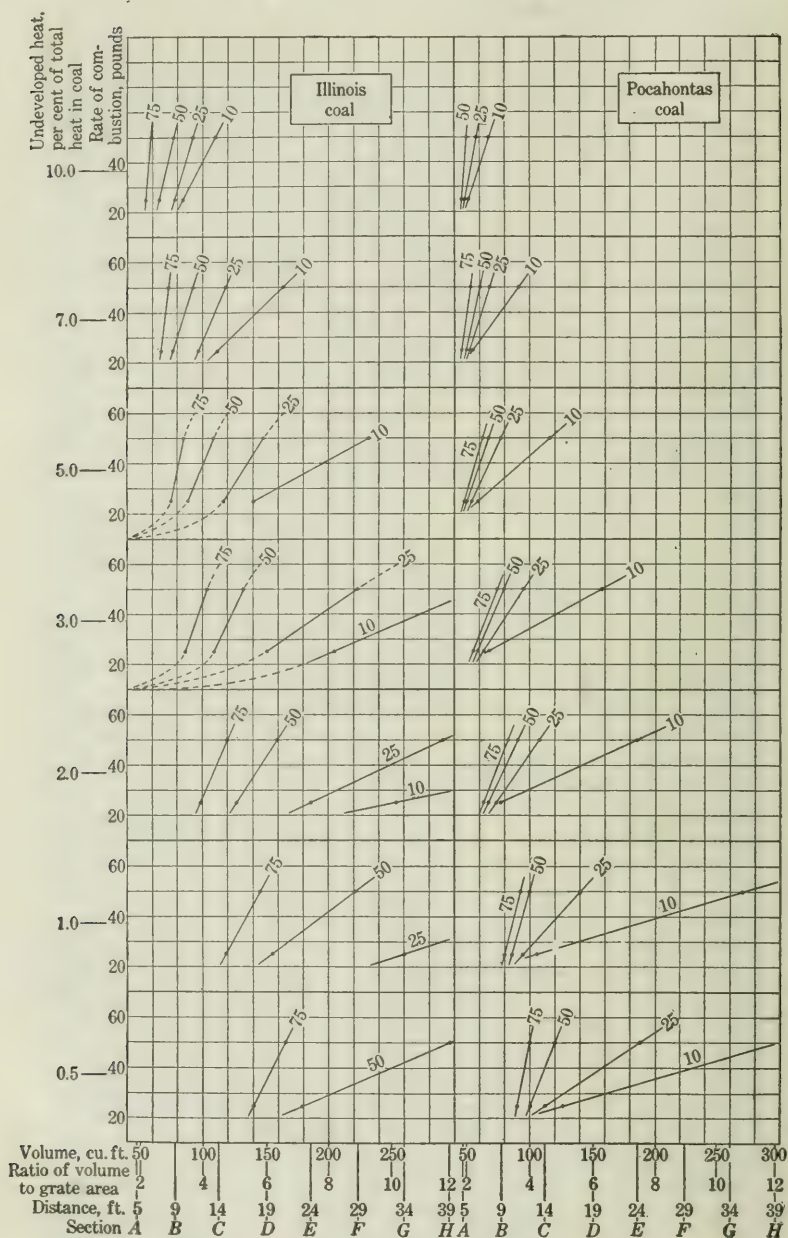


FIGURE 29.—Results of tests with Illinois and Pocahontas coal showing relation between the required size of combustion space, a given completeness of combustion, the rate of firing, and the percentage of excess air. Curves on the left are for Illinois coal; those on the right for Pocahontas coal. Figure on each curve indicates percentage of excess air; figures at left margin opposite each group of curves indicates percentage of undeveloped heat and rate of combustion. Figures at the bottom indicate volume of combustion space, ratio of volume of combustion space to grate area, length of path of gas travel, and sections at which gas samples were collected in combustion chamber.

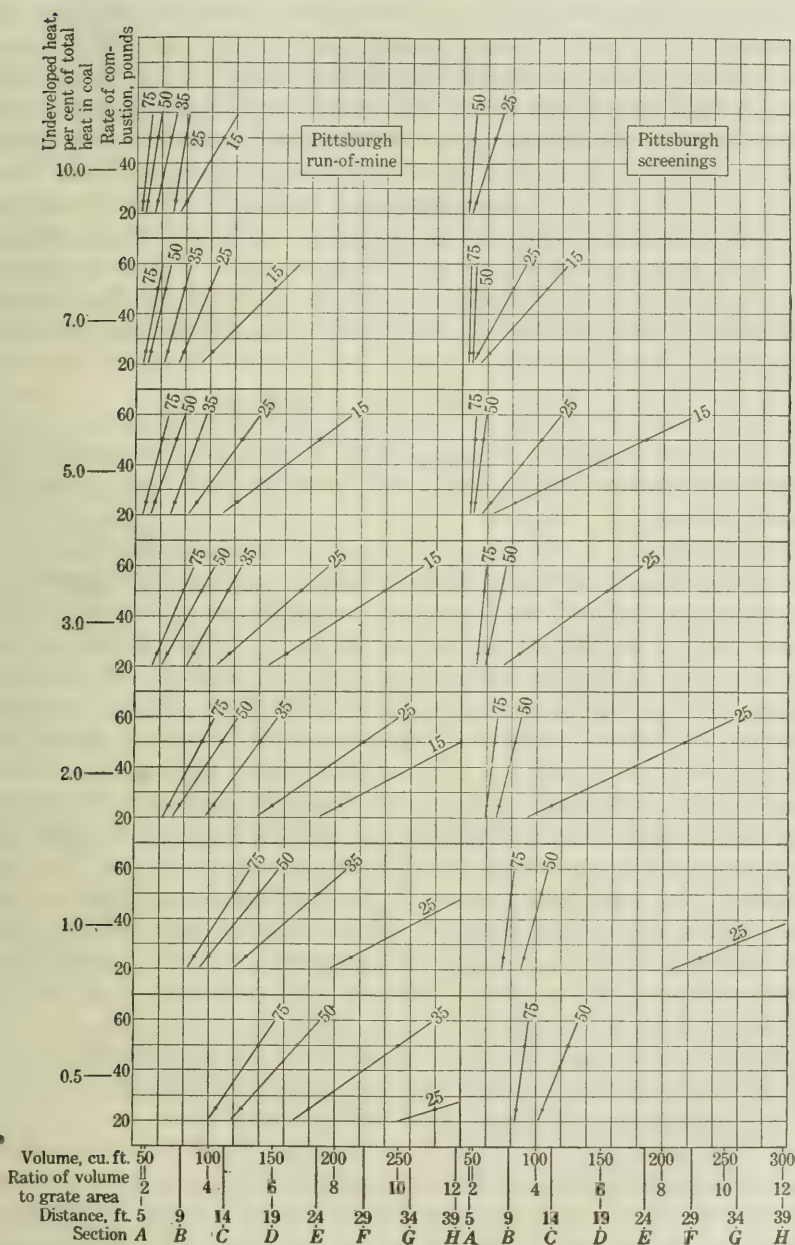


FIGURE 30.—Results of tests with Pittsburgh run-of-mine and Pittsburgh screenings showing relation between the required size of combustion space, a given completeness of combustion, the rate of firing, and the percentage of excess air. Curves on the left are for run-of-mine coal; those on the right, for screenings. Figure on each curve indicates percentage of excess air. Figures at left margin opposite each group of curves indicate percentage of undeveloped heat and rate of combustion. Figures at the bottom indicate volume of combustion space, ratio of volume of combustion space to grate area, length of path of gas travel, and sections at which gas samples were collected in combustion chamber.

however, that between the two points the curves are very nearly a straight line, and inasmuch as the two points cover the rates of combustion used in small and large power stations, the curves have considerable practical value in furnace design for the determination of the size of combustion space when other conditions are given. The curves for the first three coals are more accurate than those obtained with the Pittsburgh screenings, because with the latter not enough tests have been made to insure reliable average points. It is well to state that the series of tests with the Pittsburgh screenings was run mainly with the object of studying the combustion immediately over the fuel bed, and therefore efforts were made to obtain data for that purpose.

PRACTICAL APPLICATION OF RESULTS.

The curves of figures 29 and 30 can be used for determining the size of the combustion space required for given conditions, in the following manner:

Suppose that it is desired to design a furnace that will burn Illinois coal at the rate of 40 pounds per square foot of grate per hour with 50 per cent excess of air and with an incomplete combustion of only 2 per cent of the heat in the coal as fired. For the solution of this problem the left half of figure 29 can be used and the group of curves designated by 2 per cent (undeveloped heat) at the left margin. From the intersection point of the horizontal line of 40 pounds of rate of combustion with the curve of 50 per cent excess of air, a vertical line is followed to the bottom of the figure, where in the second scale the size of the combustion space is found to be 5.8 cubic feet to every square foot of grate. The third scale indicates that the length of gas travel for this condition should be about 18 feet. The first scale at the bottom indicates that with the experimental furnace about 145 cubic feet of combustion space was needed to satisfy the given condition, the space extending to within one foot of section D, as indicated by the lowest scale.

If Pocohontas coal is to be burned under the same condition, the required size of the combustion space is obtained from the group of curves, designated by 2 per cent (undeveloped heat), in the right half of the same figure. From the intersection point of the horizontal line of rate of combustion of 40 pounds with the curve of 50 per cent of excess of air the vertical line is followed to the bottom of the figure, where the second scale indicates that about 3.2 cubic feet of combustion space is needed for every square foot of grate area, and that the length of the gas path should be about 10 feet.

When Pittsburgh run-of-mine coal is to be burned, it is found in the same manner from the left half of figure 30 that the same results can

be obtained with a volume to grate ratio of about 3.9 and an average length of gas travel of about 12 feet.

Thus the three coals, Pocahontas, Pittsburgh, and Illinois coal, require 3.2, 3.9, and 5.8 cubic feet of space per square foot of grate respectively, to burn 40 pounds of coal per square foot of grate per hour, with 50 per cent excess of air and incomplete combustion of 2 per cent of the total heat in the coal fired.

According to the right half of figure 30, when burning Pittsburgh screenings only about 3.1 cubic feet of combustion space is required per square foot of grate to burn the coal with the same results. This is about the same combustion space as that required to burn the Pocahontas coal. The results of the tests with Pittsburgh screenings, however, are not comparable with those obtained with the other three coals because with the Pittsburgh screenings the mixing of the gases was much better. As stated on page 76 the series of tests with the Pittsburgh screenings was undertaken in order to study the combustion immediately over the fuel bed. For that purpose nine sampling tubes were inserted through the arch into the space over the fuel bed. The arch was a double one with an air space between its two parts, as shown in figure 3. This air space was connected with that supplying air to the tuyères, so that the air between the two parts of the arch was under the same pressure as the air entering the tuyères. The holes in the arch for the insertion of the sampling tubes were unavoidably made somewhat larger than the tubes, with the result that air leaked around the sampling tube from the air space between the two parts of the arch into the furnace. Leakage through the outer arch was prevented by packing asbestos rope around the tube, but there was no effective way of preventing the leakage in the inner arch. As a result of this leakage there were nine small streams of air injected into the furnace and evenly distributed over the area of the grate so that the air mixed readily with the combustible gases, thus making the combustion over the fuel bed more rapid than was the case with the other series of tests where there was no leakage through the arch. The series of tests with the Pittsburgh screenings shows the effect of mixing on the rapidity of combustion.

EFFECT OF LENGTH OF GAS TRAVEL ON THE COMPLETENESS OF COMBUSTION.

When considering the volume of combustion space, it is well to add that the length of the gas travel is probably an important factor. It seems that a long narrow combustion space is more efficient in burning the gases than a short wide one having the same cubical space. In the long narrow space the gases travel with a higher velocity, which promotes mixing and therefore quickens the combustion. In the short wide space the gases remain the same length of time, but

travel slower. On account of this slower movement the gases are less agitated and tend to travel in stratified streams. Therefore there is less mixing and the combustion is slower. It is advisable that in using the data of figures 29 and 30 in designing a furnace the path of the gases should be made nearly as long as in the experimental furnace if practicable.

EFFECT OF COMPOSITION OF COAL ON THE SIZE OF COMBUSTION SPACE REQUIRED.

Coals having different composition require different sizes of combustion space. The chemical characteristics that are most likely to affect the size of the combustion space required for a given set of conditions are the quantity and quality of the volatile matter. The quantity of the volatile matter is shown by its percentage as determined by the proximate analysis. The quality of the volatile matter is indicated approximately by the ratio of volatile carbon to available hydrogen, and probably also by the oxygen content of the coal on a moisture and ash free basis. The principal chemical characteristics of the three coals tested are given in Table 4 following. Items 1, 6, and 7 of the table give the three mentioned factors which are most likely to affect the burning qualities of any coal. Roughly speaking, the characteristics of the three coals as given in items 1 and 6 increase in about equal steps from Pocahontas to Pittsburgh, and from Pittsburgh to Illinois coal. On the other hand, the difference in the oxygen content between the Pittsburgh and the Illinois coal is much larger than it is between the Pocahontas and the Pittsburgh coal.

TABLE 4.—*Chemical characteristics of the three coals tested.*

Item No.	Item.	Pocahontas coal.	Pittsburgh coal.	Illinois coal.
1	Volatile matter in moisture and ash free coal.....per cent..	18.05	34.77	46.52
2	Fixed carbon in moisture and ash free coal.....do....	81.95	65.23	53.48
3	Carbon in moisture and ash free coal.....do....	90.50	85.7	79.7
4	Volatile carbon in moisture and ash free coal.....do....	8.55	20.47	26.22
5	Available hydrogen in moisture and ash free coal.....do....	3.96	4.70	3.96
6	Ratio of volatile carbon to available hydrogen.....do....	2.16	4.35	6.6
7	Oxygen in moisture and ash free coal.....do....	3.32	5.59	10.93
8	Nitrogen in moisture and ash free coal.....do....	1.19	1.73	1.70
9	Percentage of moisture accompanying 100 per cent of moisture and ash free coal.....do....	2.53	2.88	22.07
10	Volatile matter times the ratio of volatile carbon to available hydrogen (product of items 1 and 6).....per cent..	39.0	151	307
11	Ratio of oxygen to total carbon, in moisture and ash free coal.....do....	.0367	.0652	.137
12	Total moisture in furnace per pound of coal reduced to moisture and ash free basis.....pounds..	.409	.501	.700

THE EFFECT OF THE QUANTITY OF THE VOLATILE MATTER.

Table 5 gives the size of the required combustion space for the three coals and several sets of conditions indicated by columns 1, 2, and 3 of the table. Examination of the values in columns 4, 5, and 6

shows that the size of the combustion space does not increase in direct proportion to the percentage of the volatile matter in the coal. The increase in the combustion space from Pittsburgh to Illinois coal is much larger than the increase from Pocahontas to Pittsburgh coal. Roughly speaking, under the same conditions Pittsburgh coal requires about 20 per cent larger combustion space than Pocahontas coal, whereas Illinois coal requires about 40 per cent larger combustion space than Pittsburgh coal. That the size of the combustion space does not increase in direct proportion to the percentage of volatile matter in the coal is shown graphically by the upper curves of figure 31. If the relation of the size of combustion space to the percentage of volatile matter were a direct proportion, the relation would be represented by a straight line. The figure shows that the curves are far from straight lines, and become more and more curved as conditions of less complete combustion are considered and the combustion space becomes smaller. However, in the opposite direction toward complete combustion the curves seem to approach a straight line.

That the size of the required combustion space under ordinary degrees of completeness of combustion does not vary in direct proportion as the quantity of the volatile matter, even if the quality of the latter remains constant, can be deduced from Table 5 by comparing the two rates of combustion of the same coal. Thus, when the rate of combustion is doubled the quantity of the volatile matter distilled per unit of time is doubled. However, to burn this double quantity of volatile matter with the same excess of air to the same completeness, the combustion space is increased only about 20 per cent. Table 5 follows.

TABLE 5.—*Size of combustion space required for the three coals when burned under conditions given in columns 1, 2, and 3.*

Completeness of combustion, per cent of undeveloped heat.	Rate of combustion, pounds per square foot of grate per hour.	Excess of air (per cent).	Cubic feet of combustion space per square foot of grate area.		
			Pocahontas.	Pittsburgh.	Illinois.
1	2	3	4	5	6
5	50	50	2.7	2.9	4.3
3	50	50	3.2	3.7	5.3
2	50	50	3.6	4.4	6.3
1	50	50	4.0	5.6	8.9
0.5	50	50	4.8	6.8	11.9
5	25	50	2.0	2.2	3.5
3	25	50	2.3	2.7	4.35
2	25	50	2.7	3.1	5.1
1	25	50	3.4	4.0	6.2
0.5	25	50	4.0	5.0	7.1

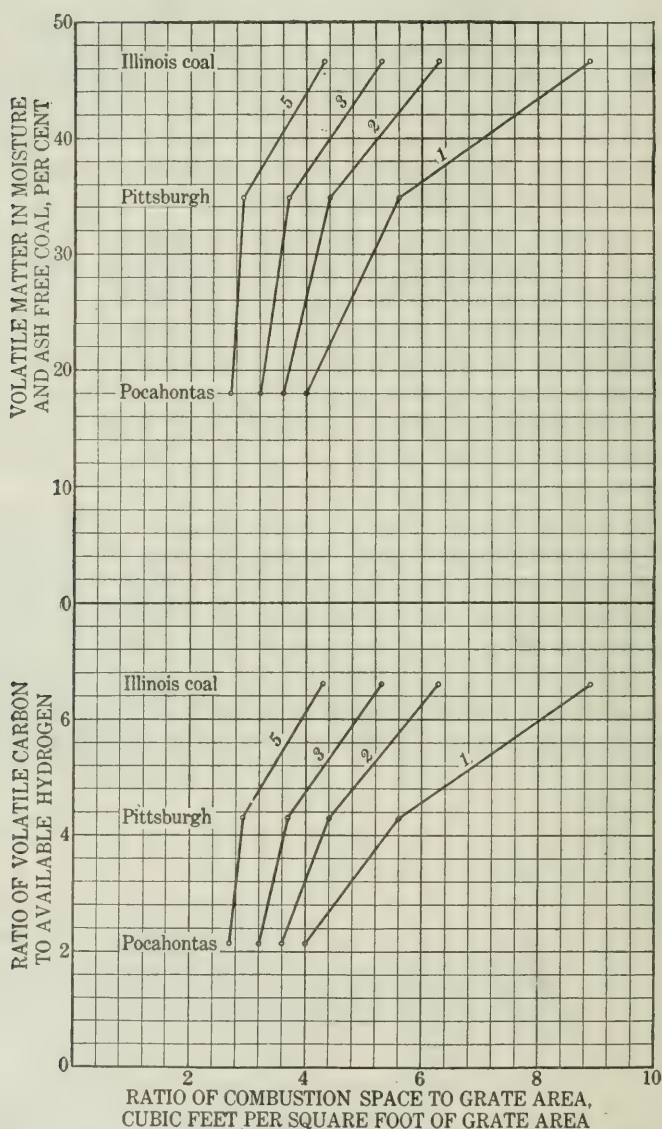


FIGURE 31.—Relation between volatile matter of coal and size of combustion space required. The curves are plotted from the first set of data in Table 5. Upper group shows relation between the size of required combustion space and the percentage of volatile matter; lower group shows relation between the size of required combustion space and the quality of the volatile matter as shown by the ratio of volatile carbon to available hydrogen. Figure near each curve indicates percentage of heat not developed, owing to incomplete combustion. In all tests the rate of combustion is 50 pounds and the excess of air 50 per cent.

THE EFFECT OF THE QUALITY OF THE VOLATILE MATTER.

The quality of the volatile combustible, as far as the ease of burning it is concerned, is perhaps best expressed by item 6 in Table 4, showing the ratio of volatile carbon to available hydrogen. These values were obtained by dividing the volatile carbon by the available hydrogen, and are probably fair indicators of the burning qualities of the coals. The amount of volatile carbon was computed by subtracting the amount of fixed carbon from that of the total carbon. The available hydrogen is equal to the hydrogen content on a moisture and ash free basis minus one-eighth of the oxygen content. The ratio shows that the volatile matter of the Pittsburgh coal contains nearly twice as much carbon and that of the Illinois coal three times as much carbon as the Pocahontas coal. These ratios indicate the probability that in burning Pocahontas coal the volatile combustible is distilled off mostly as light gases which are easily burned in the diluted furnace atmosphere, whereas in burning Illinois coal the volatile combustible leaves the fuel bed mostly as heavy hydrocarbons in the form of tars, which in the diluted oxygen of the furnace atmosphere are first decomposed into lighter hydrocarbons and carbon, the latter being precipitated as soot. This mixture of soot, tar, and gases burns slowly and requires a large combustion space for its complete combustion.

The effect of high carbon content of the carbon-hydrogen compounds on the rapidity of combustion is discussed more fully on pages 118 and 119. Here it may be repeated that in general the higher the carbon content in the carbon-hydrogen compounds the more time is required for their combustion. Therefore it may be expected that as the ratio of volatile carbon to available hydrogen increases the size of the combustion space required for a given degree of completeness also increases. The data in Table 5 and the lower set of curves of figure 31 show such an increase, but the increase is not in direct proportion to the ratio, especially with conditions of less complete combustion. As perfect combustion is approached the curve representing this relation seems to approach more nearly a straight line.

Inasmuch as both the quantity and the quality of the volatile matter exert an influence in the same direction on the burning property of a coal, the size of the combustion space required for a given completeness of combustion under a given set of conditions should vary in some rather pronounced way as the product of the quantity and the quality of the volatile matter. Such product of the percentage of volatile matter in moisture and ash free coal and the ratio of volatile carbon to available hydrogen is given in line 10 of Table 4. In the upper group of curves in figure 32 this product

is plotted against the size of combustion space shown by the first set of data in Table 5. Each curve of the upper group gives the relation

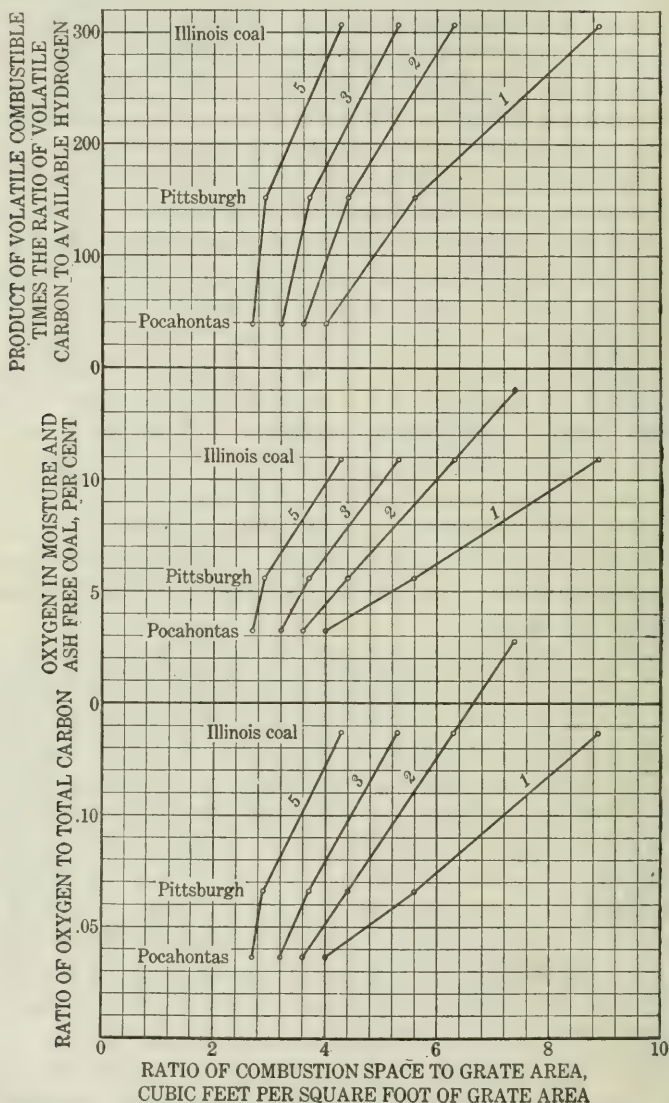


FIGURE 32.—Relation between size of combustion space required and the chemical properties of three coals. The upper group of curves has for its ordinates the product of the percentage of volatile matter times the ratio of volatile carbon to available hydrogen, from line 10, Table 4; the middle group, the percentages of oxygen in "moisture and ash free" coal, from line 7, Table 4; and the lower group, the ratio of total carbon to oxygen in "moisture and ash free" coal, from line 11, Table 4. All three groups have a common abscissa, the ratio of the combustion space to grate area, plotted from the first set of data in Table 5. Figure near each curve indicates percentage of heat not developed, owing to incomplete combustion. In all tests the rate of combustion is 50 pounds and the excess of air 50 per cent.

between the size of combustion space and the product of quantity times the quality of volatile matter for one degree of completeness

of combustion indicated by the figure near each curve. The curves are similar in form to those of figure 31, but are somewhat nearer to being a straight line, particularly the curves for more complete combustion. It may then be said that, in a rough way, when nearly complete combustion is desired the size of combustion space varies directly as the product of the quantity and the quality of the volatile matter as the two are given in items 1 and 6 of Table 4. As the combustion becomes less complete the curve showing the relation between this product and the size of the combustion space is farther from a straight line.

OXYGEN AS AN INDICATOR OF THE BURNING QUALITY OF COALS.

The ratio of the volatile carbon to available hydrogen is only one of probably several factors which may indicate the burning qualities of volatile combustible. Among the other factors the oxygen content in "moisture and ash free" coal suggests itself as the most important one.

In line 7, Table 4, the percentages of oxygen in Pocahontas, Pittsburgh, and Illinois coals are shown to be 3.32, 5.59, and 10.93, respectively. According to these figures, the Illinois coal contains by far the largest percentage of oxygen. At the present state of knowledge of combustion of coal it is difficult to explain why oxygen when contained in the volatile matter should delay its combustion. Nevertheless there are some indications that volatile combustible containing a high percentage of oxygen is harder to burn than one containing little oxygen. Whether the difficulty in burning it is due to the oxygen content or to some other chemical property can not be stated definitely. It is interesting to note that with the three coals tested the combustion space required for the same degree of completeness of combustion is almost directly proportional to the oxygen content in "moisture and ash free" coal. That is, if tests of the three coals run at the same rate of combustion, the same excess of air, and the same completeness of combustion are plotted on the oxygen contents as abscissa and the ratio of combustion space to grate area as ordinate, the curves connecting each group of three points representing the three coals are nearly straight lines. Four of such curves are given in the middle of figure 32. In the absence of more complete data the authors are inclined to believe that this nearly straight line relation between the required combustion space and the oxygen content is purely accidental. However, as some writers^a attribute to the oxygen content in coal considerable importance the authors are presenting this relation for the consideration of those interested in this subject.

^a White, David, The effect of oxygen in coal: Bull. 29, Bureau of Mines, 1911, p. 80.

The authors wish to add that it is generally conceded that the oxygen content shows to a certain measure the age of the coal—that is, it shows what stage the process of carbonization of the original plant substance has reached. On the average the original plant substance from which coal was formed contained about 40 per cent of oxygen and a comparatively low percentage of carbon. As the process of the formation of coal went on the oxygen was gradually decreased and the proportion of the carbon thereby increased. Anthracite coal contains only about 2.5 per cent of oxygen and a very high percentage of carbon. With the progress of carbonization, the percentage of the volatile matter also decreases and its quality undergoes a change which makes it easier to burn. Thus, although the oxygen content itself may not directly affect the combustion qualities of a coal it may be regarded in a way as an indicator of such qualities.

In other words, there is probably a certain chemical property of the coal which affects its combustion qualities, and this chemical property varies with the content of oxygen, although the variation in one is not the cause nor the result of the variation in the other, changes in both being brought about by the same cause, the progress of the carbonization of the plant substance.

Inasmuch as with the progress of carbonization the percentage of oxygen decreases and that of the carbon increases, it would seem that the ratio of the oxygen content to the content of total carbon would be a more direct indicator of the age of coal, and therefore also an indicator of its qualities affecting the ease of burning it in industrial furnaces. The group of curves at the bottom of figure 32 gives the relation between this ratio and the required combustion space. In the figure, this relation is represented by a nearly straight line, which fact indicates that the required combustion space increases nearly directly as the ratio; this is particularly true with the conditions giving nearly complete combustion. These curves have the same shape as those of the middle group of the figure.

That the oxygen content is a good indicator of the stage of the process of formation of coal is shown by figure 33, which is a transcription of a chart compiled by Ralston and published in Technical Paper 93^a as Plate I. In Ralston's chart thousands of analyses of coals and other fuels of the United States are plotted on trilinear coordinates representing the carbon, hydrogen, and oxygen contents in moisture-free, ash-free, nitrogen-free, and sulphur-free coal. That is, the coal is assumed to consist of only carbon, hydrogen, and oxygen, containing none of the oxygen and hydrogen which can be driven away as moisture.

^a Ralston, O. C., Graphic studies of ultimate analyses of coals: Tech. Paper 93, Bureau of Mines, 1915, 41 pp.

In the figure the small triangle represents the trilinear diagram, with each of the three coordinates running from 0 to 100. The horizontal distances are the percentages of carbon, starting at the right and ending with 100 per cent at the left-hand corner. The vertical distances are the percentages of hydrogen, beginning at the bottom of the triangle and ending with 100 per cent at the upper corner. The oxygen begins with the slanting side of the triangle as zero and runs toward the lower right-hand corner as 100 per cent. As all the coals and other fuels fall within the small shaded part of the triangle, this part is shown greatly enlarged, in order to show more in detail the position of the different coals.

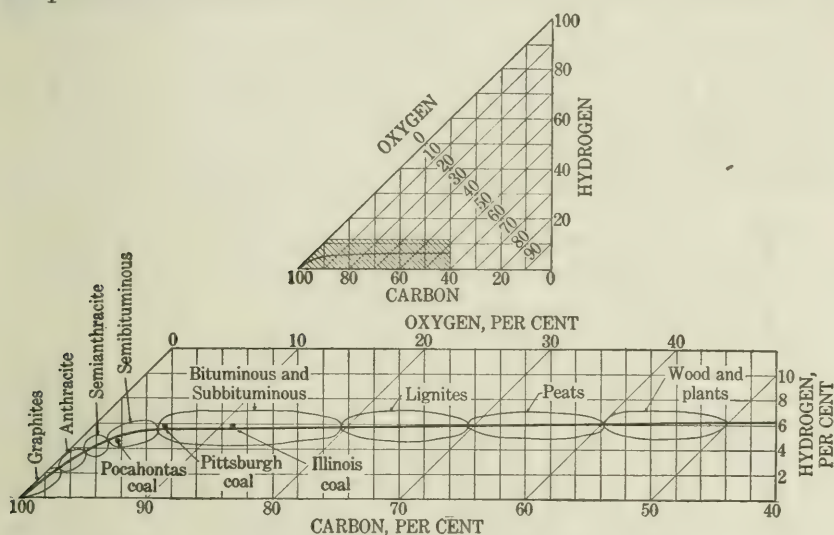


FIGURE 33.—General characteristics of various fuels and their relation as shown by their carbon, hydrogen, and oxygen contents reduced to moisture-free, ash-free, nitrogen-free, and sulphur-free basis, plotted on trilinear coordinates. Shaded area in triangle represents part covered by coals and other fuels. Trapezoid below represents this area greatly enlarged, showing the fields covered by various grades of coals and other fuels. The three black dots show the position of the three coals tested. Compare this figure with figures 31 and 32.

This enlarged part of figure 33 does not contain points representing the individual coals as given in Ralston's chart, but outlines the general grouping of the coals and the fields in which the different fuels fall on the chart. The position of each of the three coals used in tests with the long combustion chamber is indicated on the chart by a black dot designated by the name of the coal. The striking feature of the chart is the fact that, starting with wood, the oxygen content is about 42 per cent, and it gradually decreases through the peats, the lignites, subbituminous, bituminous, semibituminous, and anthracite coal to less than 2.5 per cent.

THE EFFECT OF MOISTURE IN COAL ON COMBUSTION.

Moisture in coal is another chemical characteristic which may affect the combustion. Although in moderate percentages the moisture in furnace gases may be beneficial, in large quantities it may be a detriment and reduce the velocity of combustion. Figure 34, prepared from data by Mellor,^a shows the effect of water vapor on the velocity of combustion of two volumes of CO with one volume of oxygen. The abscissas give the water vapor in per cent by volume. The ordinates are numbers proportional to the velocity of combustion. The curve shows that the maximum velocity of combustion is obtained with about 5 or 6 per cent of moisture. On either side of this maximum

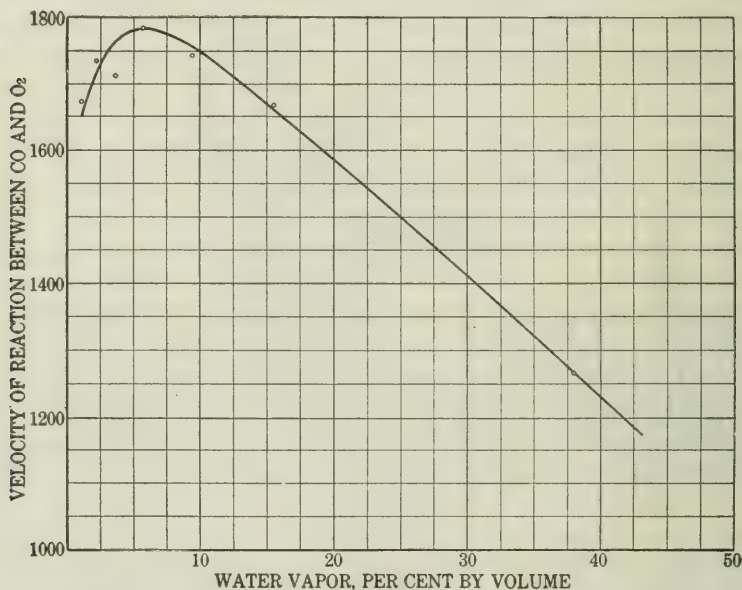


FIGURE 34.—Relation between the percentage of water vapor and the velocity of reaction between two volumes of CO and one volume of O_2 . Curve compiled from data by Mellor.

percentage the velocity of combustion drops rapidly. With no moisture present, the mixture of the two gases would not explode, showing that a small amount of water vapor is necessary for the two gases to unite.

How the presence of different percentages of moisture would affect the combustion of CO with O_2 when the two reacting gases are greatly diluted by CO_2 and N_2 can not be directly deduced from figure 34. It is possible that a curve of similar shape holds true for the combustion of CO under furnace conditions and that with the Illinois coal the furnace gases contain more moisture than the percentage giving the highest velocity of combustion. Under the conditions expressed by curve 3 in figure 31, and using Illinois coal, the percentages of the

^a Mellor, J. W., *Chemical Statics and Dynamics*, 1904, p. 471.

different constituents in the furnace are as follows: CO, 0.6; CO₂, 13.0; O₂, 4.0; H₂O, 7.0; N₂, 75.4.

Thus, although the water vapor constitutes a small percentage of the furnace gases, its volume is considerably greater than the total volume of the two reacting gases CO and O₂. It seems probable, therefore, that moisture in such high quantity retards combustion.

Considering the moisture entirely from the law of mass action, its presence in the furnace is always objectionable, because it reduces the concentration of the reacting gases. Whether it has chemically any retarding effect on the combustion when contained in large quantity can not be definitely stated, as no data on the subject except that given in figure 34 seem to be available.

The nature of combustion and of the coordinates used in figures 31 and 32 are such that none of the relations shown by the five groups of curves can really be represented by a straight line. The straight lines which occur in these figures are merely accidental and are very likely a straight part of a curve or represent only a special case of a general law.

Some of the combustible gases that are burned in the combustion space are not a part of the volatile combustible at all, but are the results of reduction of CO₂ and H₂O in the reducing zone of the fuel bed. It has been shown in experiments described in Technical Paper 137^a that even when coke containing practically no volatile matter is burned, the gases rising from a 6-inch fuel bed contain as much as 18 per cent of CO. Similar results were also obtained with anthracite coal. Inasmuch as the air needed to burn this CO is usually added some distance above the surface of the fuel bed, the gases may have to pass through a considerable volume of combustion space before they are thoroughly mixed with the air and burned. Thus, although these fuels do not have any volatile matter, some combustion space must be provided for mixing the CO with air and burning it. Therefore, in going from the lower grade of coals to Pocahontas coal and coke, the combustion space required does not decrease as fast as the factors indicating the burning properties of the fuel. For this reason a curve representing any set of conditions may appear as a straight line in the region of low-grade coals, but in the low-volatile fuels it has a perceptible curvature. This curvature is always in the direction that makes the combustion space larger.

There is no fuel that will burn almost completely without any combustion space. No matter how much the volatile content of the coal is decreased, the combustion space can not be decreased beyond certain limits except at the expense of completeness of combustion.

^a Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces: Technical Paper 137, Bureau of Mines, 1916, p. 43.

RELATION BETWEEN KIND OF COAL USED AND THE COMPLETENESS OF COMBUSTION.

Table 6 following shows the relation between the kinds of coal and the completeness of combustion for six sets of conditions, given in columns 1, 2, and 3. The degree of completeness of combustion is indicated by the percentage of undeveloped heat. The values in the last three columns show that there is no simple relation. Sometimes the difference in incomplete combustion is greater between Pocahontas and Pittsburgh coal, and sometimes the difference is greater between Pittsburgh and Illinois coal. The degree of the completeness of combustion seems to depend on what part of a curve the three points are placed by the conditions governing the combustion.

TABLE 6.—*Relation between the kind of coal and the completeness of combustion when other conditions are constant.*

Rate of combustion, pounds per square foot of grate per hour.	Excess of air (per cent).	Cubic feet of combustion space per square foot of grate area.	Undeveloped heat, per cent of total heat in coal.		
			Pocahontas.	Pittsburgh.	Illinois.
50	75	4.0	0.5	1.7	3.4
50	50	4.8	.5	1.7	4.0
50	25	7.5	.5	2.6	4.0
25	75	3.6	.5	1.0	2.9
25	50	4.0	.5	1.0	4.0
25	25	4.5	.5	2.5	5.2

DETERMINATION OF THE SIZE OF THE COMBUSTION SPACE OF A FURNACE TO BURN A GIVEN COAL.

Figure 32 can be used as a guide to design furnaces for burning given coals. Suppose that it is desired to design a furnace for each of the three coals given in Table 7, the combustion to be complete to within 2 per cent when the coal is burned at the rate of 50 pounds per square foot of grate per hour and with 50 per cent excess of air. The analyses of the coals have been taken at random from Bulletin 23^a. In the table, lines 7, 13, and 14 give the factors indicating the burning qualities of the three coals. By the use of these three factors and figure 32 the size of the combustion space can be approximately determined. Thus with the New Mexico coal the percentage of oxygen given in line 7, Table 7, is 14.02. The point on the prolonged curve marked 2, in the middle set of curves in figure 32, representing this percentage, shows that the size of combustion

^a Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coals and related investigations, Sept. 1, 1904, to Dec. 31, 1908: Bull. 23, Bureau of Mines, 1912, 380 pp.

space required for the given condition is 7.4 cubic feet to each square foot of grate. The product of the quantity and the quality of the volatile combustibles given in line 13, Table 7, and curve 2 of the top group in figure 32 show that the furnace should have about 6.7 cubic feet of combustion space to each square foot of grate area. The ratio of the oxygen to total carbon given in line 14, Table 7, and curve 2 of the lowest group in figure 32 show that 7.4 cubic feet of combustion space is needed for each square foot of grate. The position of the three points on the diagram is shown by the small circle on the upper end of curve 2 in each group. Thus the ratio of the combustion space to the grate area as given by the three factors varies from 6.7 to 7.4.

Similarly the size of the combustion space of a furnace to burn the Virginia coal under the given conditions is indicated by determining the points representing the three factors of lines 7, 13, and 14 (Table 7) on curve 2 of the respective groups in figure 32. In this instance the three factors indicate that the required combustion space per square foot of grate area should be 4.9 to 5.1 cubic feet.

For the New River, W. Va., coal the three factors indicate that the ratio of the combustion space to the grate area varies from 3.7 to 3.9.

TABLE 7.—Composition of three given coals and factors indicating their burning qualities.

PROXIMATE ANALYSIS OF COAL AS RECEIVED.

Line.	Item.	New Mexico coal.	Virginia coal.	New River (W. Va.) coal.
1	Moisture.....per cent..	11.90	3.37	1.85
2	Volatile.....do...	37.85	33.75	20.31
3	Fixed carbon.....do...	41.57	56.41	73.87
4	Ash.....do...	8.68	6.47	3.95

ULTIMATE ANALYSIS OF MOISTURE AND ASH FREE COAL.

5	Carbon.....per cent..	78.48	84.70	88.50
6	Hydrogen.....do...	5.52	5.32	5.02
7	Oxygen.....do...	14.02	7.53	4.28
8	Nitrogen.....do...	1.28	1.55	1.55
9	Sulphur.....do...	.70	.90	.65

PROXIMATE ANALYSIS OF MOISTURE AND ASH FREE COAL.

10	Volatile.....per cent..	47.6	37.5	21.55
11	Fixed carbon.....do...	52.4	62.5	78.45

FACTORS INDICATING BURNING QUALITIES.

12	Volatile carbon+available hydrogen.....	6.9	5.1	2.24
13	Product of lines 10 and 12.....	327	191	48.3
14	Line 7+line 5.....	0.178	0.089	0.049

THE MOST ECONOMICAL AIR SUPPLY FOR A GIVEN FURNACE AND GIVEN FUEL.

For a given furnace and a given fuel there is a certain percentage of excess air which gives the maximum over-all efficiency of a steam-generating apparatus. If the supply of air is increased beyond this percentage the over-all efficiency drops because of the heat lost in heating this extra air. If, on the other hand, the air supply is decreased below this best percentage, the heat losses increase on account of less complete combustion. These are the two principal causes of heat not being available for a boiler and the ones that are affected by air supply. The percentage of excess air giving the lowest sum of these two combined losses varies with the size of the combustion space and the kind of coal. When the combustion space is large smaller air excess is necessary to obtain good combustion than when the combustion space is small. With coals having low percentages of volatile matter less excess air is needed for nearly complete combustion than with coals having high percentages of volatile matter. Figures 35 to 39, inclusive, show that these statements are true. These figures were compiled from figures 24 to 30, inclusive. In figures 35 to 38 the abscissas are the percentages of air in excess of the amount theoretically needed to oxidize completely all carbon to CO_2 and all hydrogen to H_2O . The lower scale gives the corresponding percentages of CO_2 in the products of combustion. The ordinates are the percentages of heat not available for the boiler. The straight inclined line gives the quantity of heat that it takes to raise the temperature of the dry air, supplied for combustion, from atmospheric temperature to the temperature of saturated steam under 150-pound gage pressure. The dotted curves in the lower part of the figure give the undeveloped heat in the gaseous combustible at the end of that part of the combustion space having a ratio to the grate area indicated by the figure at each curve. Thus, for example, the curve designated by 3 represents a furnace having 3 cubic feet of combustion space to every square foot of grate area, and so on. Each of the solid curves in the upper part of the figure give the sum of the quantities of heat shown by the straight line and one of the dotted curves; that is, it shows the quantity of heat not available for the boiler due to both incomplete combustion and the sensible heat in the dry furnace gases. The heat in the moisture of the coal and that formed by the burning of hydrogen does not vary with the air supply and therefore does not affect the shape nor the horizontal position of these curves. Similarly the change in the boiler pressure does not change the slope of the straight line; it merely raises or lowers the line. Inasmuch as it is desired to show the minima in the upper curves, or in other words the percentage of excess air giving

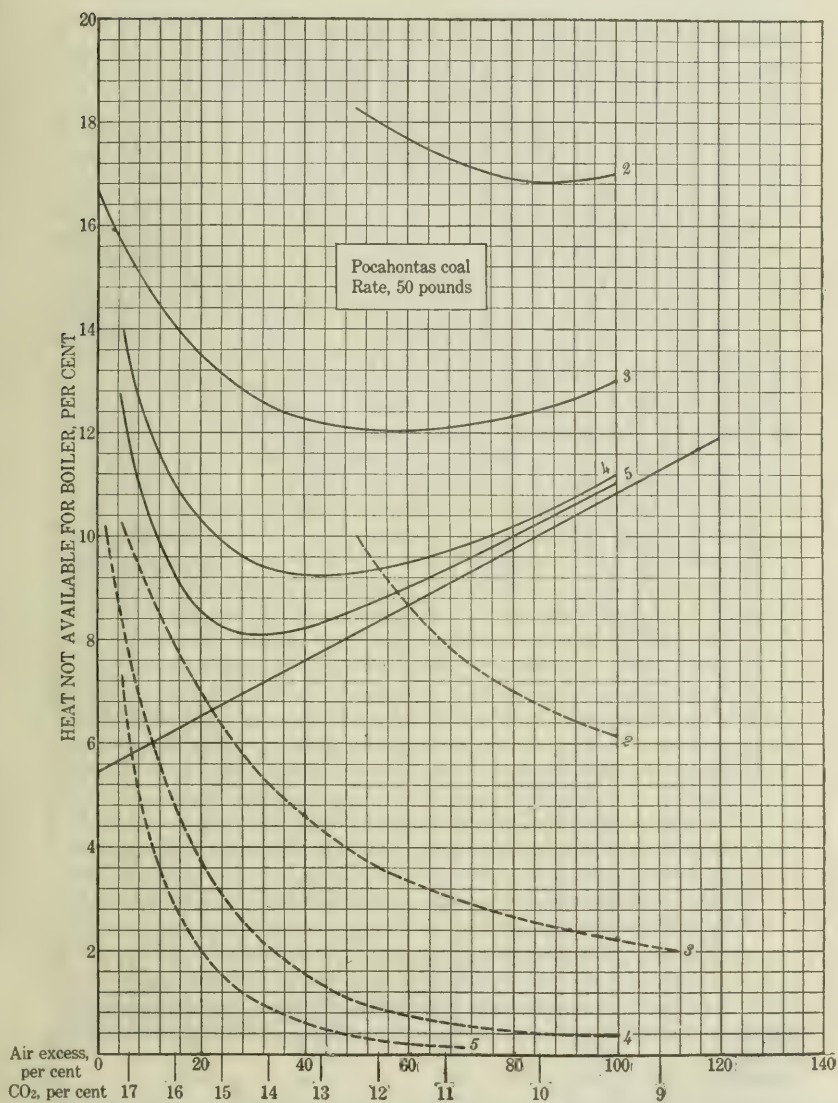


FIGURE 35.—Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Pocahontas coal; rate of firing, 50 pounds. The straight inclined line indicates the increase in quantity of heat absorbed in heating the air supply from atmospheric temperature to the temperature of steam in the boiler. The dotted curves show percentage of heat not developed, owing to incomplete combustion, in a furnace having the ratio of combustion space to grate area indicated by the figure near each curve. The solid-line curves represent the sum of the heat losses shown by the straight line and each of the dotted curves, and show what the excess of air should be for the minimum heat losses in a given furnace.

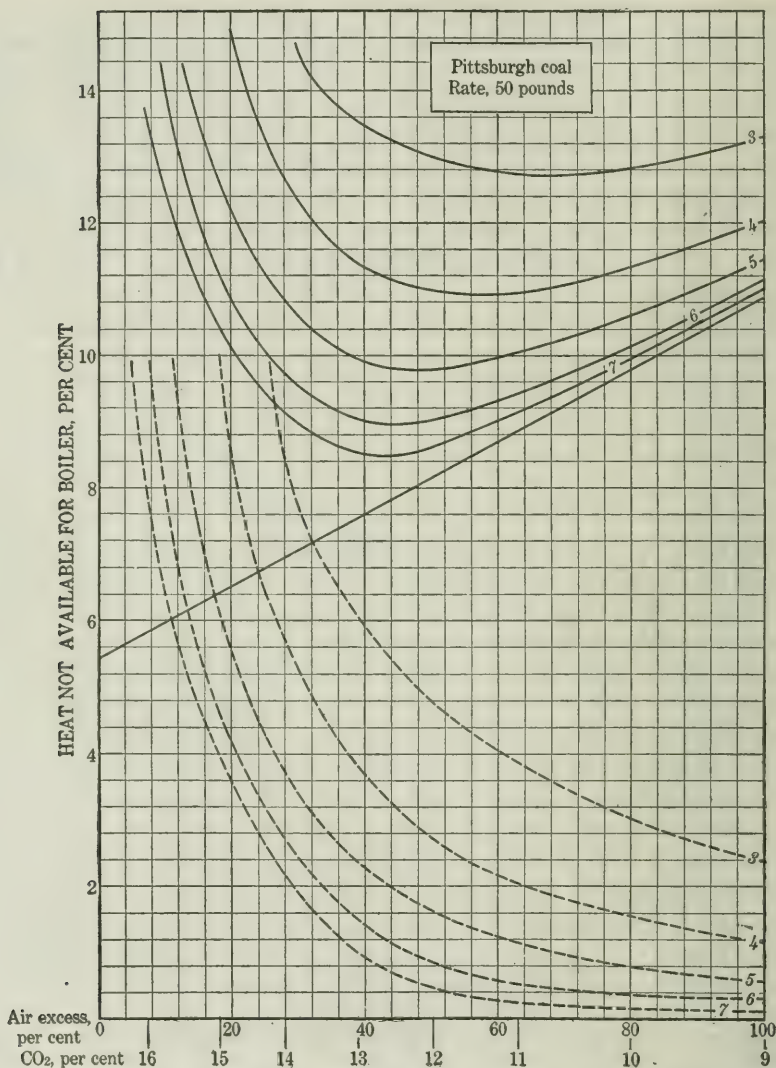


FIGURE 36.—Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Pittsburgh coal; rate of firing, 50 pounds. The straight inclined line indicates the increase in quantity of heat absorbed in heating the air supply from atmospheric temperature to the temperature of steam in the boiler. The dotted curves show percentage of heat not developed, owing to incomplete combustion, in a furnace having the ratio of combustion space to grate area indicated by the figure near each curve. The solid-line curves represent the sum of the heat losses shown by the straight line and each of the dotted curves, and show what the excess of air should be for the minimum heat losses in a given furnace.

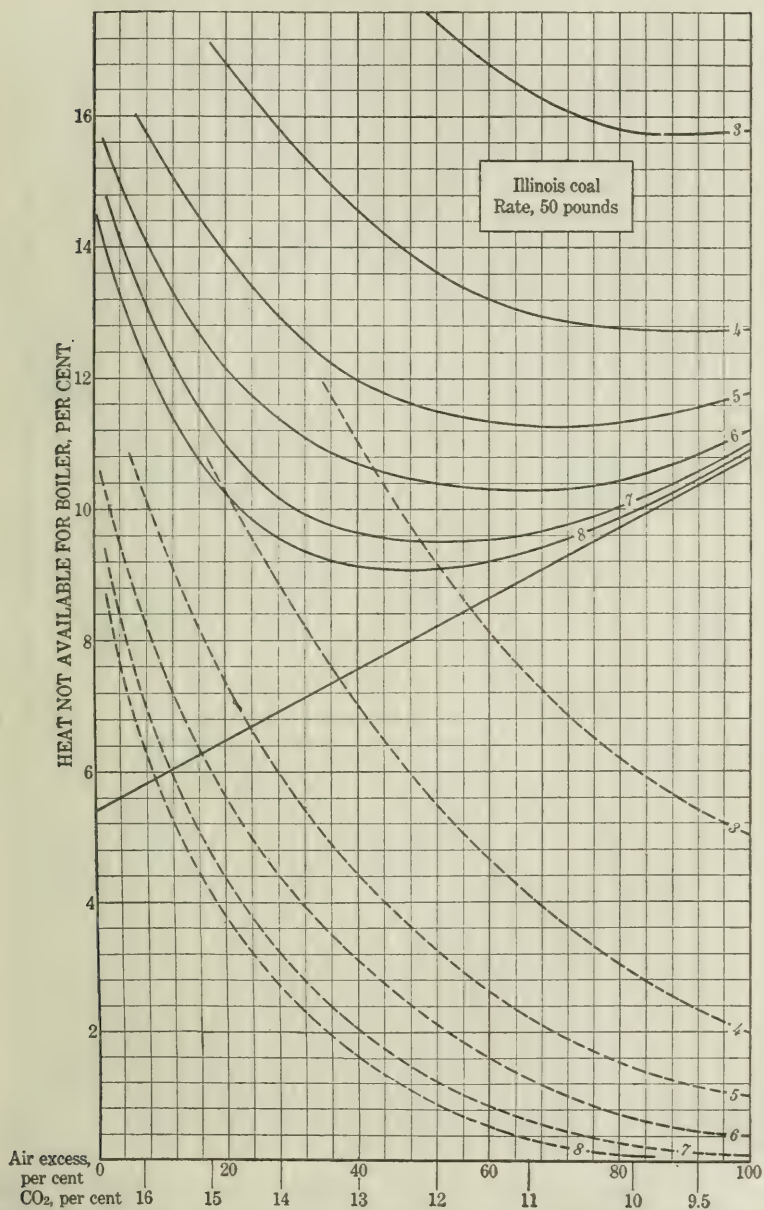


FIGURE 37.—Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Illinois coal; rate of firing, 50 pounds. The straight inclined line indicates the increase in quantity of heat absorbed in heating the air supply from atmospheric temperature to the temperature of steam in the boiler. The dotted curves show percentage of heat not developed, owing to incomplete combustion, in a furnace having the ratio of combustion space to grate area indicated by the figure near each curve. The solid-line curves represent the sum of the heat losses shown by the straight line and each of the dotted curves, and show what the excess of air should be for the minimum heat losses in a given furnace.

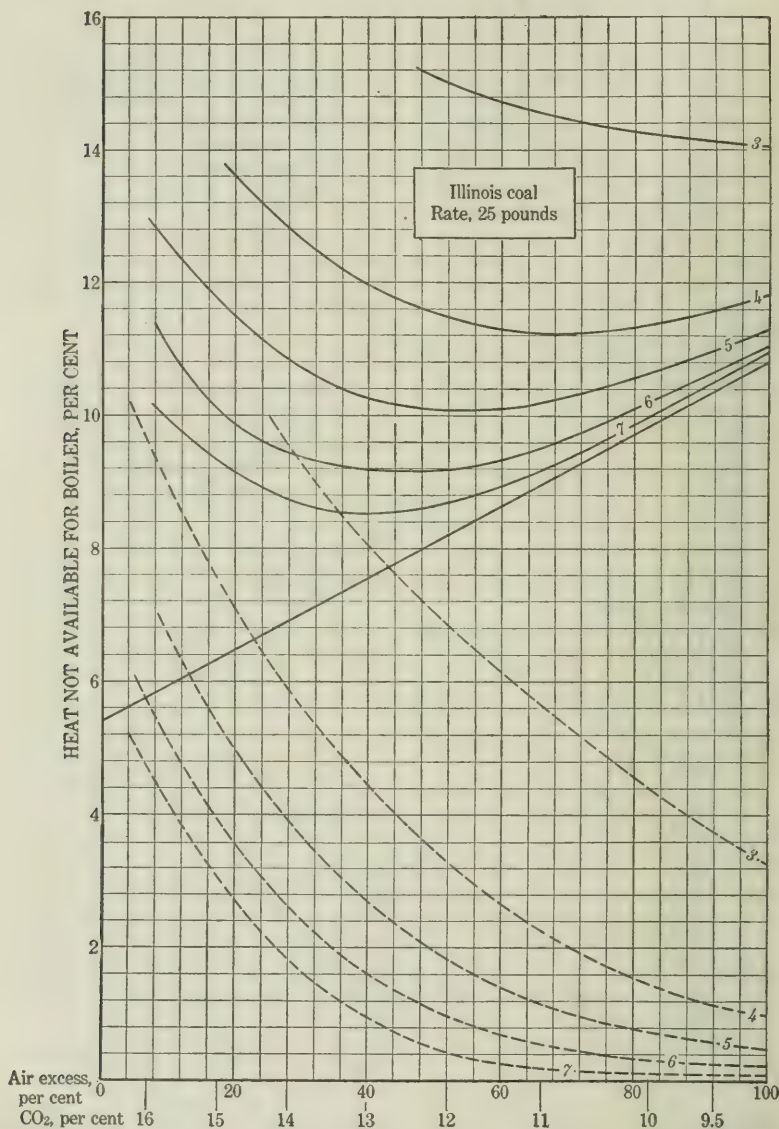


FIGURE 38.—Effect of air supply on the two principal sources of heat loss in a steam-generating apparatus as shown by tests of Illinois coal: rate of firing, 25 pounds. The straight inclined line indicates the increase in quantity of heat absorbed in heating the air supply from atmospheric temperature to the temperature of steam in the boiler. The dotted curves show percentage of heat not developed, owing to incomplete combustion, in a furnace having the ratio of combustion space to grate area indicated by the figure near each curve. The solid-line curves represent the sum of the heat losses shown by the straight line and each of the dotted curves, and show what the excess of air should be for the minimum heat losses in a given furnace.

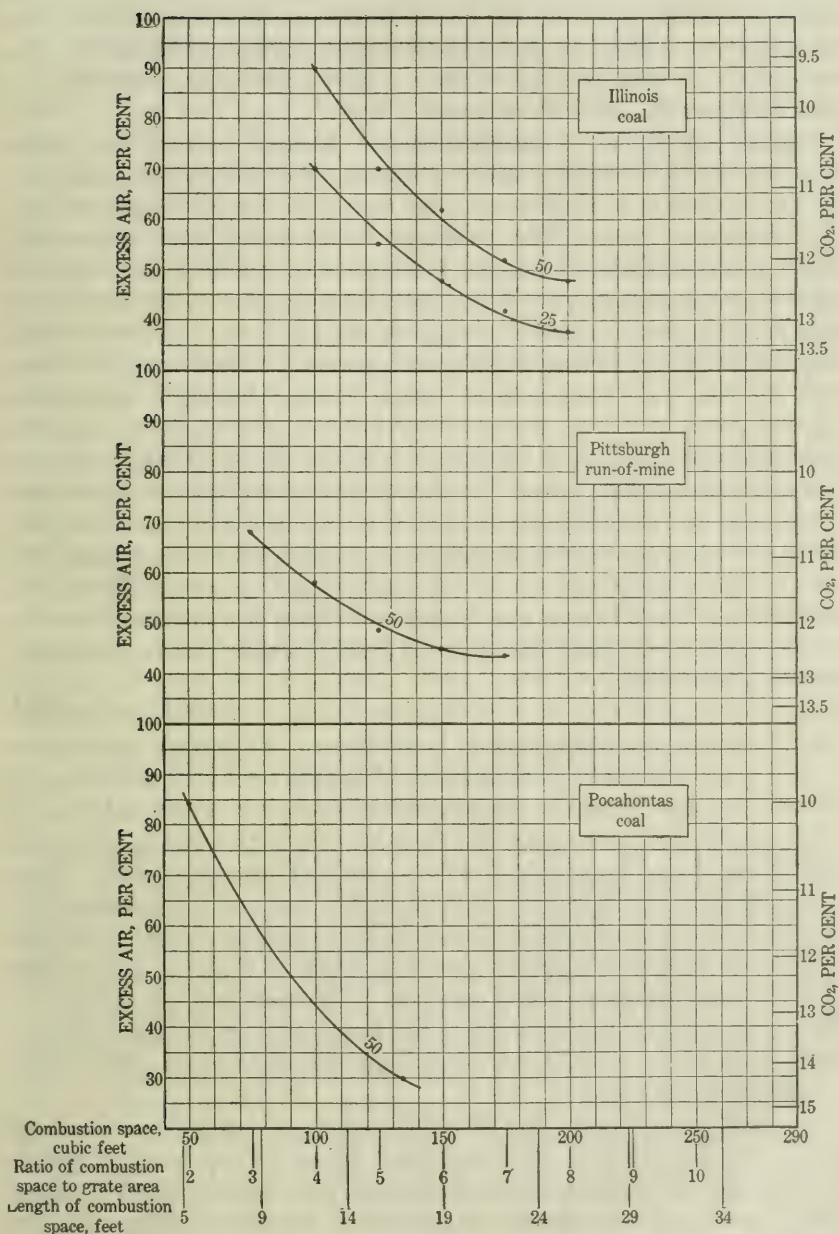


FIGURE 39.—Curves showing percentage of excess air giving the minimum heat losses in burning Pittsburgh, Pocahontas, or Illinois coal in various sizes of combustion space. Proportions of combustion space given by the scales at the bottom. Scale at right indicates percentage of CO₂ in furnace gases for any given excess of air shown by scale at left. Figure near each curve indicates the rate of firing the coal in pounds per square foot of grate per hour.

the least losses, and therefore the best results, the moisture and the steam pressure need not be taken into consideration in compiling such curves. That is, only those losses directly affected by the excess of air are considered here. These losses are expressed in percentage of the calorific value of coal.

The upper curves of figures 35 to 38, inclusive, show that as the size of the combustion space increases the minimum losses are obtained with a lower excess of air and a higher percentage of CO_2 in the furnace gases. The minimum losses in the furnace having a small combustion space are much larger than the minimum losses in the furnace equipped with a large combustion space. However, with the large combustion space the minimum losses extend over a much smaller range of excess air than they would with a small combustion space. This means that with a furnace having a large combustion space more skill is required to keep its performance within the narrow range of minimum losses or maximum efficiency than to operate a small furnace at its best. With the furnace having a small combustion space a variation of 50 to 100 per cent in the excess of air, and even more, makes very little difference in the performance of the furnace. However, the maximum efficiency of the furnace having a large combustion space is so much higher than that of the furnace with a small combustion space that there is little doubt left as to which furnace is preferable.

Figures 35, 36, and 37 were prepared from tests of the three different coals at the same rate of combustion—50 pounds per square foot of grate per hour. Comparison of the curves in the three figures shows that with the same size of combustion space considerably more air is needed for the best results when burning high-volatile coal, such as Illinois, than when using the low-volatile Pocahontas coal. Thus with a furnace having 5 cubic feet of combustion space per square foot of grate area the best results with the Illinois coal were obtained when the excess of air was about 70 per cent, whereas with the Pocahontas coal the best results required only about 30 per cent of excess air. However, this best performance with Illinois coal appears to be about 3 per cent of the total heat in coal lower than the best results with the Pocahontas coal.

To show the effect of the rate of combustion on the excess of air giving the best results under a boiler, figure 38 has been prepared. This figure gives the conditions for the best results when burning Illinois coal in the experimental furnace at the rate of 25 pounds per square foot of grate per hour. Comparison of figure 38 with figure 37 shows that with the lower rate of combustion the minimum heat losses occur with somewhat smaller excess of air and the losses are a little lower.

Figure 39 shows the relation between the size of the combustion space and the percentage of excess air giving the best results under

a steam boiler. The figure consists of three separate diagrams having common abscissas, each diagram giving the relation for one of the coals tested. The diagram for the Illinois coal, given at the top of the figure, has two curves, one for a rate of combustion of 50 pounds, and one for a rate of 25 pounds, of coal per square foot of grate per hour. The other two diagrams show only one curve for a rate of combustion of 50 pounds. The scale on the left gives the percentage of excess air and the scale on the right the corresponding percentage of CO_2 in the furnace gases. The size of the combustion space at the bottom of the chart is given by the three scales. Reading from the top the first scale gives the combustion space in cubic feet, the second scale below gives the number of cubic feet of combustion space for each square foot of grate area, and the third scale is the average length of the path of gas travel through the combustion space.

The most important feature shown by figure 39 is that different furnaces and different fuels require different percentages of excess air to give the best results. This means that there is no one definite percentage of CO_2 in the furnace gases that will give the best results in every furnace burning any coal. Some furnaces and some fuel may give best results with high percentages of CO_2 , whereas others may have to be operated with a comparatively low CO_2 content. Figure 39 may furnish a guide as to the probable best CO_2 content for a given furnace and a given coal.

DISCUSSION OF MISCELLANEOUS DATA.

STRATIFICATION OF GASES.

There seems to be a considerable tendency for furnace gases to flow in stratified streams through the combustion space. The stratification occurs in spite of the whirling of the gases above the fuel bed of the Murphy furnace. The whirling was plainly visible through a peephole in the side wall of the Heine boiler. This whirling motion is caused by the two streams of air coming in through the tuyères and the stream of gases rising from the center of the fuel bed. It seems to continue for some distance beyond the fuel bed. The motion, and the three streams of gases causing it, are shown in figure 7. It would seem that such a motion would cause the gases to form a uniform mixture a short distance beyond the fuel bed. That such is not the case is shown by the variation in the composition of gas samples taken simultaneously at different points of the same cross section, as shown in Table 8, which gives the analyses of all the gas samples taken in test 188, and Table 9, giving the analyses of samples taken in test 195. In each table column 1 gives the section and column 2 the location of the sampler within the section where the gases were collected.

TABLE 8.—Results of analysis of individual gas samples collected in test 188, with Pittsburgh screenings. Rate of combustion 38 pounds.

Section of furnace where sample was taken.	Location of sampler within section.	Percentage, by volume, of—								Tar, grams per cubic foot of gas at 60° F. and 30-inch pressure.	Soot, grams per cubic foot of gas at 60° F. and 30-inch pressure.
		CO ₂ .	Unsaturated hydrocarbons.	O ₂ .	CO.	CH ₄ .	H ₂ .	N ₂ .	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12
At surface of fuel bed	L-24	7.5	0.4	0.9	18.8	1.4	10.0	61.0	30.8		
Do.	L-40	8.7	.0	4.2	9.6	.4	5.1	72.0	15.1		
Do.	L-56	5.1	.0	14.2	.9	.0	2	79.6	1.1		
Do.	M-24	1.3	.0	.4	33.1	.2	3.6	61.4	36.9		
Do.	M-40	1.8	.0	.0	32.1	.0	2.6	63.5	34.7		
Do.	M-56	8.6	.0	12.0	.0	.0	.1	79.3	.1		
Do.	R-24	10.5	.0	3.2	7.6	.3	3.1	75.3	11.0		
Do.	R-40	9.2	.3	6.5	5.2	.9	5.6	72.3	12.0		
Do.	R-56	11.6	.0	8.5	.1	.0	.1	79.7	.2		
Average		7.1	.1	5.5	11.9	.4	3.4	71.6	15.8	0.107	0.080
11 inches above fuel bed.	L-24	10.6	.0	5.4	3.1	.0	2.6	78.3	5.7		
Do.	L-40	8.5	.0	1.2	11.3	1.9	9.9	67.2	23.1		
Do.	L-56	14.0	.0	.8	4.0	.1	1.9	79.2	6.0		
Do.	M-24	2.8	.0	.2	29.5	.2	4.4	62.9	34.1		
Do.	M-40	10.2	.0	3	16.0	.0	3.0	70.5	19.0		
Do.	M-56	10.0	.0	6.4	5.9	.1	1.6	76.0	7.6		
Do.	R-24	8.8	.0	8.4	1.0	.0	1.6	80.2	2.6		
Do.	R-40	9.8	.0	6.8	1.4	.2	1.2	80.6	2.8		
Do.	R-56	11.5	.0	6.6	.8	.0	.2	80.9	1.0		
Average		9.6	.0	4.0	8.1	.3	2.9	75.1	11.3	0.013	0.284
22 inches from fuel bed.	M-24	12.1	.0	1.7	10.2	.1	1.9	74.0	12.2		
Do.	M-40	12.1	.0	2.2	8.1	.1	1.5	76.0	9.7		
Do.	M-56	12.8	.0	3.2	5.6	.0	1.3	77.1	6.9		
Average		12.3	.0	2.4	8.0	.1	1.6	75.6	9.6		
Section A.	L-5	15.6	.0	2.0	1.3	.0	.4	80.7	1.7		
Do.	L-16	12.1	.0	.2	8.4	.1	3.4	75.8	11.9		
Do.	L-21	.8	.1	.0	32.7	.1	4.5	61.8	37.3		
Do.	M-5	15.1	.0	3.8	1.0	.0	.5	79.5	1.5		
Do.	M-16	14.4	.0	2.3	5.7	.0	1.4	76.2	7.1		
Do.	M-21	.6	.1	.0	33.4	.1	4.6	61.2	38.1		
Do.	R-5	13.3	.0	5.9	.3	.0	.1	80.4	.4		
Do.	R-16	14.3	.0	2.0	2.6	.0	1.2	79.9	3.8		
Do.	R-21	.1	.1	.1	33.7	.0	4.2	61.8	37.9		
Average		14.2	.0	2.7	3.2	.0	1.2	78.7	4.4	0.014	0.160
Section C.	L-5	14.6		4.6	.1	.0	.1	80.6	.2		
Do.	L-16	15.3		3.1	.4	.0	.2	81.0	.6		
Do.	L-27	14.3		4.3	.1	.0	.2	81.1	.3		
Do.	M-5	14.9		3.5	.4	.0	.1	81.1	.5		
Do.	M-16	14.4		3.7	.3	.0	.1	81.5	.4		
Do.	M-27	14.0		3.9	.2	.0	.0	81.9	.2		
Do.	R-5	12.1		7.0	.1	.0	.0	80.8	.1		
Do.	R-16	15.0		3.2	.3	.0	.1	81.4	.4		
Do.	R-27	13.9		4.7	.3	.0	.1	81.0	.4		
Average		14.3		4.2	.2	.0	.1	81.2	.3		
Section E.	L-5	13.8		5.0	.0	.0	.0	81.2	.0		
Do.	L-16	14.8		3.8	.2	.0	.0	81.2	.2		
Do.	L-27	14.9		3.7	.2	.0	.0	81.2	.2		
Do.	M-5	14.0		4.8	.1	.0	.0	81.1	.1		
Do.	M-16	14.7		3.7	.4	.0	.0	81.2	.4		
Do.	M-27	14.3		4.5	.4	.0	.0	80.8	.4		
Do.	R-5	13.7		5.2	.1	.0	.0	81.0	.1		
Do.	R-16	15.0		3.4	.3	.0	.0	81.3	.3		
Do.	R-27	11.7		7.3	.3	.0	.0	80.7	.3		
Average		14.1		4.6	.2	.0	.0	81.1	.2		

TABLE 8.—Results of analysis of individual gas samples collected in test 188, with Pittsburgh screenings. Rate of combustion 38 pounds—Continued.

Section of furnace where sample was taken.	Location of samples within section.	Percentage, by volume, of—								Tar, grams per cubic foot of gas at 60° F. and 30-inch pressure.	Soot, grams per cubic foot of gas at 60° F. and 30-inch pressure.
		CO ₂ .	Unsaturated hydrocarbons.	O ₂ .	CO.	CH ₄ .	H ₂ .	N ₂ .	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12
Section G.....	L- 5	14.8	.....	3.5	.3	.0	.0	81.4	.3	.....	.....
Do.....	L-16	15.0	.....	3.5	.2	.0	.0	81.3	.2	.....	.....
Do.....	L-27	14.9	.....	3.6	.3	.0	.0	81.2	.3	.....	.....
Do.....	M- 5	14.8	.....	3.6	.3	.0	.0	81.3	.3	.....	.....
Do.....	M-16	14.1	.....	4.3	.2	.0	.0	81.4	.2	.....	.....
Do.....	M-27	14.9	.....	3.6	.3	.0	.0	81.2	.3	.....	.....
Do.....	R- 5	13.1	.....	5.4	.1	.0	.0	81.4	.1	.....	.....
Do.....	R-16	15.0	.....	3.4	.3	.0	.0	81.3	.3	.....	.....
Do.....	R-27	14.8	.....	3.5	.4	.0	.0	81.3	.4	.....	.....
Average.....		14.6	.....	3.8	.3	.0	.0	81.3	.3	.....	.....

TABLE 9.—Results of analysis of individual gas samples collected in test 195, with Pittsburgh screenings. Rate of combustion 24 pounds.

Section of furnace where sample was taken.	Location of sampler within section.	Percentage, by volume, of—								Tar, grams per cubic foot of gas at 60° F. and 30-inch pressure.	Soot, grams per cubic foot of gas at 60° F. and 30-inch pressure.
		CO ₂ .	Unsaturated hydrocarbons.	O ₂ .	CO.	CH ₄ .	H ₂ .	N ₂ .	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12
At surface of fuel bed...	L-24	5.1	0.4	0.0	22.2	1.3	11.8	59.2	35.7	0.190	0.259
Do.....	L-40	13.6	.0	.5	5.0	.0	2.3	78.6	7.3	.022	.194
Do.....	L-56	7.4	.0	.2	16.9	.5	9.5	65.5	26.9	.038	.344
Do.....	M-24	2.7	.0	.2	31.5	.4	6.4	58.8	38.5	.....	.....
Do.....	M-40	7.8	.0	2.8	16.6	.4	2.2	70.2	19.2	.....	.....
Do.....	M-56	12.9	.0	5.0	3.9	.1	.7	77.4	4.7	.....	.....
Do.....	R-24	9.2	.1	.4	16.5	.9	4.6	68.3	22.1	.059	.068
Do.....	R-40	10.4	.1	1.3	10.7	1.0	6.1	70.4	17.9	.006	.032
Do.....	R-56	10.6	.2	.6	8.1	1.1	7.4	72.0	16.8	.004	.182
Average.....		8.9	.1	1.2	14.6	.6	5.7	68.9	21.0	.054	.180
11 inches above fuel bed.	L-24	13.2	.0	1.7	4.4	.4	1.7	78.6	6.5	.009	.197
Do.....	L-40	7.8	.0	.2	17.9	.5	6.5	67.1	24.9	.009	.152
Do.....	L-56	14.6	.0	.6	2.8	.0	1.6	80.4	4.4	.028	.284
Do.....	M-24	6.3	.0	.3	23.8	.1	4.2	65.3	28.1	.....	.....
Do.....	M-40	10.6	.0	1.9	13.4	.3	1.9	71.9	15.6	.....	.....
Do.....	M-56	12.6	.0	1.0	10.2	.2	1.7	74.3	12.1	.....	.....
Do.....	R-24	10.3	.0	5.2	1.9	.6	1.1	80.9	3.6	.003	.083
Do.....	R-40	8.9	.0	8.8	.0	.0	.1	82.2	.1	.006	.120
Do.....	R-56	12.7	.0	3.1	3.0	.2	1.1	79.9	4.3	.004	.178
Average.....		10.8	.0	2.5	8.6	.3	2.2	75.6	11.1	.010	.169
22 inches from fuel bed..	M-24	11.7	.0	7.5	1.2	.0	.2	79.4	1.4	.....	.....
Do.....	M-40	12.5	.1	6.9	.4	.0	.2	79.9	.7	.....	.....
Do.....	M-56	10.8	.0	8.6	.2	.0	.0	80.4	.2	.....	.....
Average.....		11.7	.0	7.7	.6	.0	.1	79.9	.8	.....	.....

TABLE 9.—*Results of analysis of individual gas samples collected in test 195, with Pittsburgh screenings. Rate of combustion 24 pounds—Continued.*

Section of furnace where sample was taken.	Location of sampler within section.	Percentage, by volume, of—								Tar, grams per cubic foot of gas at 60° F. and 30-inch pressure.	Soot, grams per cubic foot of gas at 60° F. and 30-inch pressure.
		CO ₂ .	Unsaturated hydrocarbons.	O ₂ .	CO.	CH ₄ .	H ₂ .	N ₂ .	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12
Section A.....	L-10	15.1	.0	2.4	.7	.0	.5	81.3	1.2	.002	.075
Do.....	L-21	11.5	.0	5.3	2.7	.1	.8	79.6	3.6	.001	.040
Do.....	M-10	13.7	.0	.5	8.4	.2	1.5	75.7	10.1	.002	.072
Do.....	M-21	16.1	.0	1.7	2.7	.1	.7	78.7	3.5	.001	.068
Do.....	R-10	14.2	.0	1.2	4.9	.3	.8	78.6	6.0	.003	.183
Do.....	R-21	10.6	.0	1.1	8.4	.5	3.9	75.5	12.8	.013	.327
Average.....		13.5	.0	2.0	4.6	.2	1.4	78.3	6.2	.004	.128
Section C.....	L- 5	12.3		6.2	.4	.0	.0	81.1	.4		
Do.....	L-16	16.3		1.3	.8	.0	.2	81.4	1.0		
Do.....	L-27	15.5		2.5	.8	.0	.2	81.0	1.0		
Do.....	M- 5	16.1		2.1	1.0	.0	.5	80.3	1.5		
Do.....	M-16	15.8		1.5	1.5	.1	.5	80.6	2.1		
Do.....	M-27	14.6		3.0	1.0	.0	.6	80.8	1.6		
Do.....	R- 5	14.7		3.9	.5	.0	.1	80.8	.6		
Do.....	R-16	15.8		2.2	.7	.0	.2	81.1	.9		
Do.....	R-27	15.3		2.9	.4	.0	.3	81.1	.7		
Average.....		15.2		2.8	.8	.0	.3	80.9	1.1		
Section E.....	L- 5	13.1		5.4	.2	.0	.1	81.2	.3		
Do.....	L-16	16.2		1.4	.8	.0	.4	81.2	1.2		
Do.....	L-27	16.2		1.7	.6	.0	.1	81.4	.7		
Do.....	M- 5	15.8		2.9	.0	.0	.0	81.3	.0		
Do.....	M-16	16.0		1.6	.8	.0	.3	81.3	1.1		
Do.....	M-27	16.2		1.6	.8	.0	.3	81.1	1.1		
Do.....	R- 5	16.4		1.4	1.3	.0	.3	80.6	1.6		
Do.....	R-16	16.1		1.1	1.8	.0	.7	80.3	2.5		
Do.....	R-27	16.1		1.2	1.8	.0	.6	80.3	2.4		
Average.....		15.8		2.0	.9	.0	.3	81.0	1.2		
Section G.....	L- 5	16.1		1.6	1.1	.0	.3	80.9	1.4		
Do.....	L-16	15.1									
Do.....	L-27	16.0		1.7	.9	.0	.2	81.2	1.1		
Do.....	M- 5	15.8		1.7	1.1	.0	.3	81.1	1.4		
Do.....	M-16	16.1		1.3	1.3	.0	.5	80.8	1.8		
Do.....	M-27	16.4		1.3	1.1	.0	.4	80.8	1.5		
Do.....	R-16	16.2		1.0	1.5	.0	.6	80.7	2.1		
Do.....	R-27	15.7		1.5	1.5	.0	.5	80.8	2.0		
Average.....		15.9		1.4	1.2	.0	.4	81.1	1.6		

Sections A to G are vertical; the three sections preceding section A in the tables are nearly horizontal planes parallel to and directly over the surface of the fuel bed. In Table 8 the first group of nine gas samples was taken just at the surface of the fuel bed; the second group was taken 11 inches above the fuel bed; and the third group of three samples 22 inches above the fuel bed. In column 2 the letters L, M, and R stand for left, middle, and right sampler, respectively. The figure following each letter indicates the distance of the intake of the sampler from the inside of the front wall. Thus, L-40 means that the sample was collected with the sampler on the left, 40 inches from the inside of the front wall. The position of the left, middle, and

right samplers is shown in figure 4 (p. 15). Only three samples were collected at the section 22 inches above the fuel bed.

In the series of tests shown in Table 9 only six samples were collected at section A, because the samplers were constructed for collecting tar and soot samples and for that reason each sampler contained only two gas sampling tubes. Beyond section A every alternate section was omitted on this series. The position of the samplers at section A is shown in figure 5 (p. 16). The position of the sampler in the furnace and the distance of the intake of the sampler from the arch is designated similarly to Table 8.

All the sections are nearly at right angles to the path of the gases; above the fuel bed where the gases flow nearly vertically the sections are horizontal; in the combustion chamber where the gases flow horizontally the sections are vertical.

Table 8 shows that even beyond section A in the combustion chamber the gases tend to flow in stratified streams, apparently without any regard to their specific weight. In general, near the roof of the combustion chamber the gases contain high percentages of oxygen and very little combustible; near the bottom they contain high percentages of combustible and very little free oxygen. This rather regular distribution of oxygen at the top and combustible gases at the bottom would seem to indicate that there is a predominance of horizontal layers in the stream of furnace gases. The vertical layers are much more irregular, showing that there is some change of gas from side to side.

This predominance of horizontal layers in the furnace gases as they flow through the combustion chamber is perhaps shown more markedly in Table 10, which gives the excess of air, calculated as shown on page 28, for each sample of gas. The designation of the position of the samplers is similar to that in Tables 3, 8, and 9. In the tests of Table 10 no samples were taken before section A and no tars and soot samples were collected. Nine gas samples were collected at section A.

All the samples collected 5 to 7 inches below the arch show, as a rule, considerable excess of air, whereas the samples collected near the bottom show small excess or even deficient air supply. This difference in the excess of air becomes smaller as the gases flow through the combustion space, until at section H the mixture of gases becomes fairly homogenous.

Tables 4 and 10 demonstrate that it is much more difficult to obtain the average gas sample than it is to analyze it. This is a similar conclusion to the one arrived at from tests described in Bulletin 97.^a

^a Kreisinger, Henry, and Ovitz, F. K., Sampling and analysis of flue gases; Bull. 97, Bureau of Mines, 1915, 70 pp.

TABLE 10.—Results showing percentages of excess air calculated for individual simultaneous gas samples, showing stratification of gases.

[Tests with Illinois coal.]

Section of furnace chamber where sample was taken.	Position of sample within section.	Percentage of excess air in samples represented by test No.—																
		165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181
Section A.	L-5.....	98.2	296.5	301.3	325.2	103.1	312.5	260.7	119.2	683.1	301.3	95.8	300.3	70.0	391.7	.....	.....	.....
	L-16.....	0.9	6.3	69.4	109.7	69.4	17.3	17.4	40.5	58.0	30.1	50.4	21.6	0.0	68.9	.....	.....	414.0
	L-27.....	—	28.0	43.3	17.3	40.7	33.0	—	36.4	51.8	43.1	20.5	55.6	42.0	46.4	.....	.....	10.7
	M-5.....	38.9	213.7	285.2	192.0	76.4	302.8	285.7	52.2	621.4	189.5	38.3	178.5	8.3	290.0	.....	.....	339.9
	M-16.....	11.0	81.0	148.9	79.2	14.2	146.2	45.5	32.2	23.7	5.4	7.2	92.9	10.7	17.9	.....	.....	94.3
	M-27.....	47.2	49.1	5.4	26.7	37.5	16.3	2.2	27.3	57.1	50.0	21.6	5.5	3.5	5.9	.....	.....	41.3
	R-5.....	—	219.2	285.2	311.4	403.5	447.9	598.8	649.6	587.3	543.3	197.6	354.8	63.7	231.0	.....	.....	321.5
Section B.	L-5.....	1.7	19.2	18.5	36.8	27.1	60.8	5.9	100.1	245.4	100.1	7.2	9.0	22.3	23.0	.....	.....	18.3
	L-16.....	—	—	51.0	12.5	54.7	43.0	39.3	11.8	41.1	45.4	45.8	56.8	41.6	45.1	.....	.....	59.0
	L-27.....	47.8	120.6	167.5	149.2	102.1	207.2	197.1	59.4	270.8	196.8	118.9	167.2	60.2	207.2	.....	.....	229.5
	L-16.....	33.0	20.6	81.5	65.4	58.8	52.7	7.9	41.6	42.3	38.0	37.6	27.5	21.0	45.4	.....	.....	20.7
	L-27.....	—	11.3	59.2	18.2	10.6	21.6	16.9	22.8	9.6	—	9.5	5.8	7.1	1.4	.....	.....	15.1
	M-5.....	40.6	146.8	197.5	207.6	87.6	235.7	179.2	30.4	293.5	163.7	36.4	181.8	18.6	196.8	.....	.....	196.8
	M-16.....	21.5	46.4	100.4	73.3	33.6	109.2	65.8	5.0	132.7	77.1	13.8	96.4	5.9	84.9	.....	.....	89.7
Section C.	M-5.....	—	14.7	39.6	23.6	8.3	55.5	3.9	—	28.5	11.3	14.1	0.6	21.4	6.6	.....	.....	12.6
	M-27.....	85.6	132.3	192.0	159.6	153.3	298.7	276.7	134.8	167.5	176.7	72.1	78.8	46.1	167.5	.....	.....	179.5
	R-5.....	—	35.3	54.2	47.4	51.3	68.7	52.9	53.1	69.3	28.8	41.5	84.0	1.0	24.8	.....	.....	41.3
	R-16.....	13.8	—	16.5	0.9	7.2	28.0	1.6	9.2	15.3	7.3	6.8	9.2	0.5	11.9	.....	.....	25.0
	L-5.....	89.6	124.0	170.9	175.6	85.6	170.9	155.3	63.9	202.1	212.9	71.5	152.7	61.6	183.0	.....	.....	202.5
	L-16.....	25.7	89.5	63.2	47.3	43.6	65.4	16.2	31.2	37.3	41.9	21.4	14.3	20.4	31.2	.....	.....	16.3
	L-27.....	—	80.1	33.9	43.6	50.5	—	1.7	17.8	18.9	1.2	1.9	10.0	15.3	8.0	.....	.....	6.2
Section D.	M-5.....	24.9	121.6	149.2	121.6	71.1	149.2	111.5	26.5	163.0	130.9	52.0	139.4	16.6	180.2	.....	.....	197.5
	M-16.....	67.5	34.6	74.9	74.9	17.6	79.0	41.9	1.5	98.5	36.1	9.1	58.8	7.4	49.7	.....	.....	33.9
	M-27.....	—	26.0	52.7	24.5	2.2	52.2	14.7	—	48.3	8.1	6.3	21.1	16.0	3.5	.....	.....	9.2
	R-5.....	—	133.0	142.9	114.6	100.2	142.9	152.1	—	114.0	136.9	82.2	217.6	11.5	113.8	.....	.....	58.8
	R-16.....	—	72.5	63.5	61.8	45.1	84.5	63.5	34.4	88.3	40.3	33.0	92.7	9.6	34.6	.....	.....	51.9
	R-27.....	—	14.1	48.1	21.8	14.6	54.2	27.0	21.1	50.4	7.9	19.5	40.1	2.1	10.9	.....	.....	11.3
	L-5.....	46.1	65.1	111.5	95.6	59.0	107.5	81.9	42.3	106.2	22.1	58.8	81.2	27.3	108.6	.....	.....	87.6
Section D.	L-16.....	11.4	35.4	89.7	63.3	34.1	82.8	36.8	19.8	71.8	52.2	11.6	41.6	26.0	52.5	.....	.....	33.6
	L-27.....	4.4	32.5	93.1	48.3	56.5	70.4	21.1	31.4	47.4	3.5	2.6	16.5	3.3	27.4	.....	.....	15.1
	M-5.....	47.3	54.8	123.4	123.4	84.2	155.6	96.6	57.4	145.2	138.3	43.2	159.3	39.7	145.5	.....	.....	109.1
	M-16.....	—	7.1	42.1	70.2	21.6	18.8	46.3	8.2	96.1	20.7	19.2	62.8	0.0	38.5	.....	.....	37.1
	M-27.....	—	13.5	46.5	87.3	18.9	68.9	28.0	9.7	63.7	4.3	5.6	35.6	0.9	12.6	.....	.....	8.1
	R-5.....	64.7	86.6	135.1	124.0	98.9	136.0	161.2	33.9	127.1	109.1	54.7	224.5	20.6	111.8	.....	.....	133.5
	R-16.....	14.6	43.5	80.4	60.4	46.3	80.4	67.7	33.9	92.5	43.5	13.9	110.2	4.7	52.0	.....	.....	72.9
R-27.....	8.1	18.0	66.5	33.0	27.1	57.4	23.7	23.8	61.8	6.5	46.5	41.4	2.7	17.2	.....	.....	9.9	

Section E.	M-5.....	18.2	39.7	93.8	80.4	73.7	109.1	87.8	104.3	109.6	52.2	101.9	25.6	111.0	.....	53.1	104.7
	Do.....	7.0	35.8	87.6	66.9	24.8	87.6	45.8	87.6	34.3	25.1	63.2	3.3	51.5	.....	9.5	36.8
	Do.....	3.3	38.0	87.8	52.4	31.5	79.0	32.7	70.0	3.3	10.1	46.4	3.0	30.0	.....	7.8	12.7
Section F.	I-5.....	14.6	42.6	91.3	79.0	44.0	87.8	60.0	87.3	83.8	85.7	64.7	36.3	106.7	148.9	36.4	59.8
	L-16.....	5.6	33.2	91.5	63.0	34.8	84.7	36.4	73.1	43.8	15.0	43.5	12.6	55.5	72.1	12.2	33.3
	I-27.....	7.9	31.1	91.3	49.5	45.1	79.5	30.1	106.4	15.3	18.4	42.9	18.8	57.4	48.0	0.1	20.9
Section G.	M-5.....	55.7	54.2	93.1	82.4	54.4	99.7	82.2	88.5	98.2	48.5	85.9	21.2	92.0	110.6	40.8	84.2
	Do.....	0.4	39.7	89.5	66.0	32.5	85.9	47.6	86.2	26.9	20.9	58.8	9.6	37.3	.....	3.1	30.8
	M-16.....	1.7	32.2	85.4	52.0	40.6	85.1	36.4	80.8	14.0	12.6	49.7	7.7	34.4	37.1	5.2	15.1
Section H.	M-27.....	23.2	49.7	97.7	72.3	64.5	90.5	82.6	90.5	73.1	50.1	122.1	11.5	71.6	108.6	37.1	94.3
	Do.....	2.9	31.7	84.0	53.6	38.7	78.4	56.3	88.0	24.4	26.2	82.8	3.6	37.8	48.9	5.3	41.6
	R-16.....	5.2	23.2	84.0	41.6	34.8	70.7	30.3	74.8	10.0	19.8	52.5	4.1	20.4	30.9	5.4	8.4
Section I.	M-5.....	26.9	42.3	104.2	80.4	56.3	90.0	67.1	75.1	79.5	52.2	84.0	22.6	85.4	.....	39.7	78.6
	Do.....	0.5	33.3	91.5	67.3	36.6	90.2	53.1	85.9	28.0	24.0	57.2	2.3	46.7	.....	2.5	36.6
	M-27.....	2.4	33.5	89.5	57.6	35.9	77.3	39.7	84.5	20.6	15.4	49.3	8.7	37.0	.....	0.8	23.4
Section J.	I-5.....	15.9	50.8	95.4	79.0	56.8	95.4	60.2	74.9	80.8	43.1	56.5	20.8	69.3	145.2	21.7	53.5
	Do.....	4.7	36.3	89.5	62.8	40.3	92.0	44.0	76.6	43.6	18.9	47.8	15.3	54.8	63.7	6.5	33.6
	L-27.....	7.4	33.5	95.9	52.9	40.3	90.5	42.1	79.9	26.2	14.3	42.5	13.1	46.1	39.6	0.9	24.9
Section K.	M-5.....	16.7	49.4	89.3	69.3	54.8	97.5	60.2	79.3	64.9	49.0	64.7	17.8	61.8	99.2	26.5	53.6
	Do.....	0.3	36.6	87.3	66.0	54.4	85.9	48.6	85.1	30.4	23.0	60.0	8.1	46.1	64.1	6.9	39.9
	M-16.....	1.5	33.3	85.4	57.2	43.2	88.0	42.5	85.4	27.6	22.2	55.7	7.0	44.0	45.5	1.2	27.0
Section L.	M-27.....	31.1	39.4	85.4	64.1	59.0	83.8	79.0	90.0	61.8	48.2	101.6	19.6	68.5	99.1	36.1	77.5
	Do.....	4.7	39.4	90.0	55.9	43.2	79.3	54.0	82.4	30.9	35.1	81.0	5.8	45.5	68.3	12.6	48.4
	R-16.....	0.1	23.2	89.7	47.1	38.9	73.7	39.5	78.6	18.0	24.8	55.1	0.4	30.8	43.3	1.0	18.0

ACCURACY OF AVERAGE COMPOSITION OF GAS SAMPLES.

The average composition of the furnace gases at any section was obtained by giving all the samples taken at one section equal weight. The individual samplers covered approximately equal areas of the cross section; and if the velocity of the gases were uniform all over the section, the volumes of gases sampled by each sampler would be the same, and an arithmetical average would give the true composition of the furnace gases at the section. However, it is certain that such was not the case. It is a known fact that when gases flow through a tube of either square or circular cross section the velocity is much higher at the center than it is near the walls. Consequently one may safely assume that in the combustion chamber the gases moved faster through the center than along the walls. Therefore the central sampler was taking gas from larger volumes than those near the walls. To obtain the correct average composition of gases, the central sampler should be given greater weight. However, obtaining any reliable figures of the respective velocities is so difficult that no attempt was made to correct for the difference in velocity. Usually eight samples were taken within 7 inches of the walls and only one in the center. Even by giving the central sample double weight the average would be changed very little.

The above reasoning and conclusion holds true for the sections beyond A, but for section A itself the conditions are somewhat different. On account of the V shape of the grate the fuel accumulates in the center of the grate to a thickness of 12 inches or more, particularly in the rear. The result is that the bottom three samplers at section A are below the level of the fuel bed. Inasmuch as section A is only about a foot from the rear end of the grate, these three bottom samplers are in a space behind the fuel bed where the gases are eddying and have a very low forward velocity as compared to the gases near the roof of the furnace. Furthermore this comparatively quiet place back of the fuel bed contains practically gases as they leave the fuel bed without any air mixed with them, all the additional air being introduced higher up above the fuel bed. The air can not in the short length of travel reach the gases in this quiet space. As a result of these conditions the bottom three samples contain much more combustible gas than the samples taken higher up. By giving the bottom samples the same weight as those higher up the average is too high in combustible gases. There is no reliable way to correct this error. As a result of it the excess of air computed from the average analysis of section A will be too low and may make it appear that air has been introduced between sections A and B.

In the series of tests of Pittsburgh screenings only six gas samples were taken at section A; three of these were about 11 inches and three 22 inches below the arch. It is believed that these six samples

gave a better average than the nine samples taken in the tests of the other three series.

RELATION BETWEEN PROPORTION OF CO₂ IN THE FURNACE GASES AND THE EXCESS OF AIR.

With each coal there is a definite relation between the percentage of CO₂ in the furnace gases and the excess of air supplied to the furnace, provided that the amount of combustible in the gases is negligible. Figure 40 shows such a relation for the four coals tested. The points for the curves are obtained by plotting the values of column 7 of Table 3 as ordinates and those of column 19 as the abscissas. All the values are based on samples of gases taken at sections G or H. All four groups of points fall closely along a smooth curve, showing that the relation is definite enough to be of practical use.

With the Pocahontas coal it is possible with 5 per cent excess of air to get a maximum of about 17 per cent of CO₂ in the furnace gases. With the Pittsburgh and Illinois coals it is possible to obtain only about 15½ per cent as the maximum with about 10 per cent excess of air. When the air is reduced below these minima, the percentage of CO₂ drops and combustible gases appear in the flue gases. This is shown by the one point in the group of the Pocahontas coal and the three points of the group of Pittsburgh screenings at the extreme left of the figure. It should be remembered that these results were obtained with a combustion space about 40 feet long. With the combustion space shorter such high percentages of CO₂ could not be obtained. With very small combustion space the maximum CO₂ content obtainable may not be over 12 per cent. That the advantages of large combustion space is appreciated by modern furnace designers is shown by the fact that at one new plant, at Connors Creek, Detroit, Mich., the combustion chamber is 33 feet high.

These facts and the discussion presented in connection with figures 35 to 39, inclusive, indicate that in the setting of horizontal tubular boilers the practice of making the gases hug the shell to increase the over-all efficiency is questionable. Of course, by squeezing the gases against the shell the heat transmission from the gases to the shell is increased; but by doing so the furnace is robbed of many cubic feet of combustion space. Rapid cooling of the gases before the combustion is complete is not desired, because such cooling retards combustion and if carried too far may even prevent it.

RELATION BETWEEN THE PERCENTAGE OF CO AND THE TOTAL COMBUSTIBLE GASES.

The relation between the percentage of CO in the furnace gases and the percentage of total combustible gases is definite enough to be of value in estimating the total combustible from the determination of

CO. Such relation is given in figure 41, each curve applying to one of the four coals tested. The relation varies slightly with the kind of

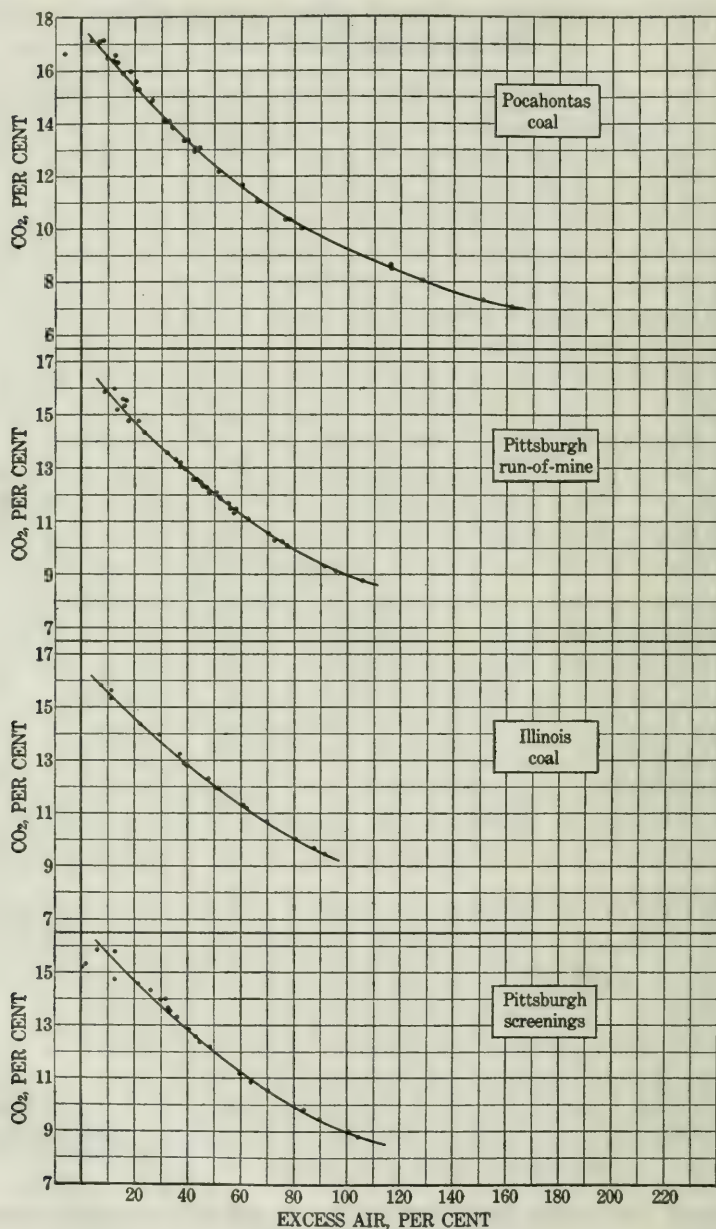


FIGURE 40.—Relation between the percentage of CO_2 in the gases and the percentage of excess of air used in combustion.

coal. Roughly speaking the CO constitutes 80 per cent of the total combustible gases; that is, when the CO content is 2 per cent the con-

tent of total combustible gases is 2.5 per cent, and when the CO content is 0.8 per cent the content of total combustible is 1.0 per cent.

The combustible gases other than CO consist largely of hydrogen; CH_4 and the unsaturated hydrocarbons constitute a very small part of the gases.

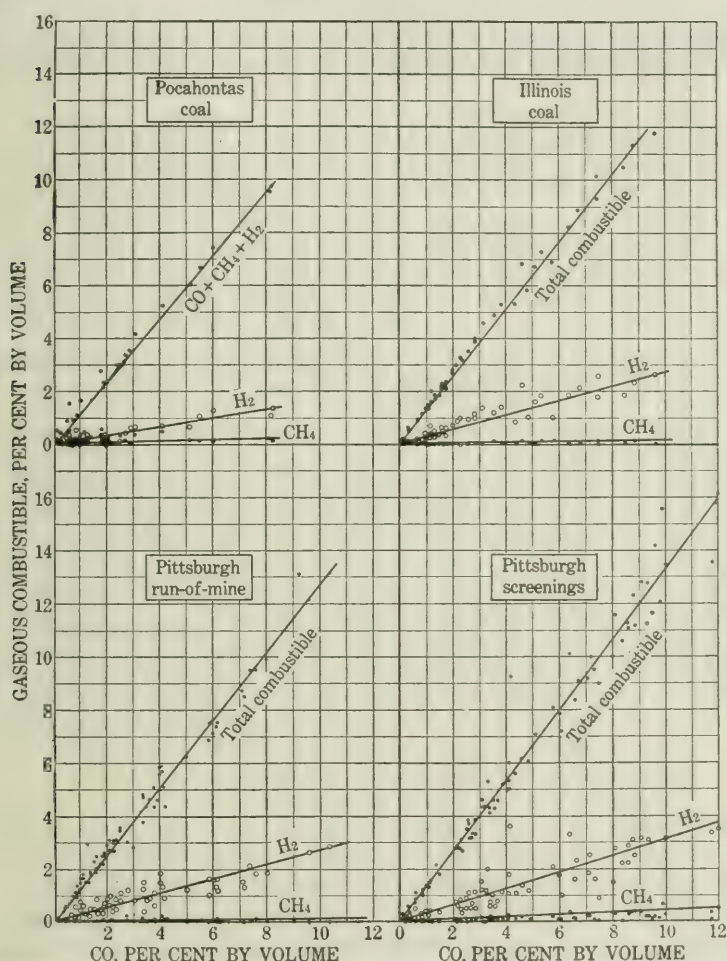


FIGURE 41.—Relation between percentages of CO and H_2 , CH_4 , and total gaseous combustible in furnace gases. Each of the group of curves is for one of the four coals tested.

The small percentage of CH_4 shown in the figure is in accordance with the nature of the gas. It has been shown by various investigators that in absence of air methane decomposes readily into hydrogen and carbon (soot) at high temperatures such as exist in furnaces.

As indicated in Table 11 (p. 113), the percentage of methane that is stable at the high furnace temperature is very low. It is doubtful if methane under ordinary furnace conditions ever reaches equilibrium. The methane content of the gases leaving the fuel bed is

probably much higher than that corresponding to equilibrium conditions, and its amount is rapidly reduced both by combustion and decomposition.

RELATION BETWEEN CO CONTENT IN GASES AND AMOUNT OF UNDEVELOPED HEAT.

Inasmuch as there is a close relation between the proportion of CO and the total gaseous combustible in the furnace gases, there is simi-

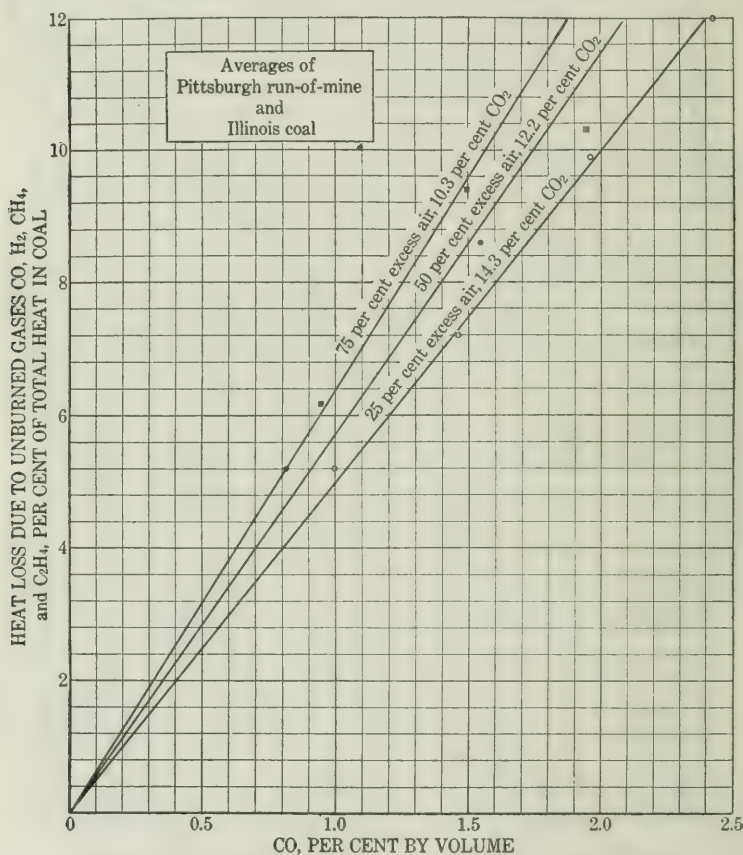


FIGURE 42.—Relation between CO content in furnace gases and heat loss due to the escape of all unburned gases.

larly a close relation between the CO content and the undeveloped heat of the gaseous combustible. This relation is definite enough so that the percentage of CO can be used to determine the heat losses due to the escape of all the unburned combustible gases from the furnace. Figure 42 shows this relation graphically. The ordinates of the figure are the undeveloped heat of the combustible gases expressed in percentage of the total heat in the coal, and the abscissas are the percentage of CO in the furnace gases. Each of the three curves show

this relation for one constant air excess, or percentage of CO_2 in the furnace gases.

Thus, supposing that the gases contain 0.6 per cent of CO and 14.3 per cent of CO_2 , or that the air excess is 25 per cent, what is the total heat loss? Starting from the point 0.6 on the scale at the bottom of figure 42, follow the vertical line to its intersection with the lowest curve; then from this point follow the horizontal line to the scale at the left, which gives the heat loss as 3 per cent of the total heat in the coal.

If the gases contain 10.3 per cent of CO_2 and 0.8 per cent of CO, then the vertical line representing 0.8 per cent CO is followed to the highest curve, and from this intersection point a horizontal line is followed to the scale at the left, which indicates the heat loss to be 5.1 per cent of the total heat in the coal. Similarly, if the content of CO_2 in the furnace gases is 12.2 per cent the middle curve is used for the determination of the heat loss.

TEMPERATURE DROP ALONG THE PATH OF GASES IN THE LONG COMBUSTION CHAMBER.

Column 17 of Table 3 shows that there is a steady temperature drop along the path of gases from section A to section G. This temperature drop is mainly due to the following causes:

(a) Some heat is absorbed from the products of combustion by the water in the gas-sampling tubes.

(b) Some heat is radiated from the walls and roof of the furnace.

(c) Some heat is radiated to the opening under the boiler.

(d) The temperature measured at section A is too high because the pyrometer was sighted on the flames, which were at a higher temperature than the gases.

HEAT ABSORBED BY WATER IN GAS SAMPLERS.

The heat absorbed by the cooling water in the gas samplers is by far the greatest cause of the temperature drop from A to G as shown by actual determination in test 179. The weight of water circulated through the samplers per hour as measured by a meter was 34,760 pounds. The rise in temperature of the water due to the absorption of heat from the furnace was 44 F. The total heat absorbed and carried away by the water was $34,760 \times 44 = 1,529,440$ B. t. u. The weight of gases passing through the furnace per hour, figured from the gas analysis and the rate of combustion, was 28,320 pounds. If the average specific heat of gases at the furnace temperature be taken as 0.2774, the heat given up by the gases for each degree of temperature drop is $28,320 \times 0.2774 = 7,856$ B. t. u. Therefore the temperature drop caused by the loss of 1,529,440 B. t. u. to the gas samplers is $1,529,440 \div 7,856 = 195^\circ \text{ F. or } 109^\circ \text{ C.}$

The high rate at which these samplers absorbed heat is worthy of note. The quantity of heat absorbed by the samplers per hour is equivalent to a rate of heat absorption of $1,529,440 \div 33,300 = 46$ boiler horsepower.

There were 16 samplers, each $1\frac{1}{8}$ inches in outside diameter and 23 inches in length, exposed to the furnace gases. This gives a total heating surface of a little under 10 square feet. Each square foot of the heating surface transmitted an amount of heat equivalent to 4.6 boiler horsepower, or one horsepower was generated on less than 0.22 square foot of heating surface.

These figures compare favorably with the figure 0.357 square foot of heating surface per boiler horsepower, which is the rate of heat transmission of the lowest row of boiler tubes at the point where the hot products of combustion first come in contact with the boiler, as determined in tests described in Technical Paper 114.^a This rate was computed from the measured temperature drop through the metal of the tube. The difference between the two figures is in the right direction. It stands to reason that the samplers absorb more heat than boiler tubes because the temperature in the furnace is higher and more heat is imparted to them by radiation than to the boiler tube.

RADIATION LOSSES FROM WALLS AND ROOF OF FURNACE.

In furnace tests described in Bulletin 8,^b it is shown that about 465,600 B. t. u. is radiated from the walls and the roof of the furnace per hour. This radiation loss reduces the temperature of the gases by $465,600 \div 7,856 = 59^\circ \text{ F.}$ or 33° C.

The heat absorbed by the cooling water in the gas samplers and the heat radiated account for 141° C. of the temperature drop of the gases at the end of the combustion chamber. There is still a drop of about 59° C. to be accounted for.

HEAT RADIATED TO OPENING UNDER BOILER.

Part of this unaccounted for temperature drop of 59° C. is due to heat radiation from the fuel bed and flames to the opening under the Heine boiler. The surfaces of the space under the boiler are at a considerably lower temperature than the flames at section A of the furnace. On account of this temperature difference the flames impart heat by radiation to these surfaces. The radiation is both direct, as shown by the straight line in figure 43, and reflected, as shown by the zigzag lines. In the latter instance the heat is radiated

^a Kreisinger, Henry, and Barkley, J. F., Heat transmission through boiler tubes: Tech. Paper 114, Bureau of Mines, 1915, p. 25.

^b Ray, W. T., and Kreisinger, Henry, The flow of heat through furnace walls: Bull. 8, Bureau of Mines, 1911, 32 pp.

from wall to wall owing to the difference of temperature between successive portions of the inner surfaces. In figure 43 these descending temperature steps are indicated by T_1 , T_2 , T_3 , and T_4 . Of course, in reality there are no such sudden steps; the high temperature gradually shades down through an infinite number of intermediate temperatures. The heat also travels in a similar zigzag manner by actual reflection from the surfaces as light does from smooth objects. It is difficult to estimate the quantity of heat transmitted from the flames to the surfaces under the boiler, and the corresponding temperature drop due to it; probably it does not exceed 25°C .

TEMPERATURE OF FLAMES AT SECTION A
HIGHER THAN AVERAGE TEMPERATURE
OF GASES AT THE SAME SECTION.

As the particles of combustible burn, the heat generated by their combustion raises the temperature of the particles immediately surrounding those in the process of combustion above those farther away, and time is required before the temperature is equalized. Thus, the flames contain centers of combustion with temperatures higher than the average temperature of the gases at the same cross section. When an optical pyrometer is used for measuring the temperature, the instrument unavoidably covers with its field some of these centers of intense combustion and gives a reading somewhat higher than the average temperature. It is difficult to estimate the error due to this cause, but in most of the measurements it probably is not over 50°F .

The temperature drop due to the first three causes mentioned is less as the rate of combustion increases. Thus comparison of figures 11 and 12 show that in test 179 having a rate of combustion of 59 pounds the drop is much less than in test 173 having a rate of combustion of 39 pounds.

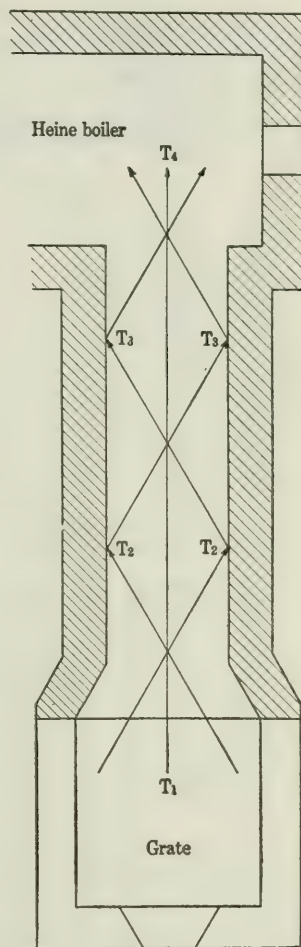


FIGURE 43.—Diagram showing temperature drop from radiation.

DISCUSSION OF THE PROCESS OF COMBUSTION ABOVE THE FUEL BED.

The weights of the combustible gases, tar, and soot in the furnace gases for a number of tests with Pittsburgh screenings are shown in Table 11 following:

TABLE 11.—Results showing weights of combustible gases, tar, and soot rising from fuel bed, in grams per cubic foot of gas at 60° F. and 50 inches pressure.

[All tests made with Pittsburgh screenings.]

Test No.	Rate of combustion, pounds.	Pounds of air per pound of combustible fired.	Distance of sample from fuel bed. ^a	Combustible gases, grams per cubic foot.					Tar, grams per cubic foot.	Soot, grams per cubic foot.	Total soot and tar, grams per cubic foot.	Total combustible, grams per cubic foot.	Soot and tar, percentage of total combustible.
				C in CO.	CH ₄ .	H ₂ .	Unsaturated hydrocarbons.	Total gaseous combustible.					
1	2	3	4	5	6	7	8	9	10	11	12	13	14
195	21.0	11.8	0	2.211	0.105	0.140	0.035	2.491	0.054	0.180	0.234	2.725	8.6
			11	1.250	.071	.071	.....	1.392	.010	.169	.179	1.571	11.4
			A	.668	.036	.036	.....	.740	.004	.128	.132	.872	15.1
207	21.4	17.8	0	1.197	.071	.071	.142	1.481	.723	.301	1.024	2.505	40.9
			11	.489	.036	.018	.....	.543	.003	.089	.092	.635	14.5
			A	.340	.018	.014	.....	.372	.001	.054	.055	.427	12.9
206	21.4	21.2	0	1.157	.071	.036	.035	1.299	.020	.064	.084	1.383	6.1
			11	.605	.018	.018	.....	.641	.005	.075	.080	.721	11.1
			A	.402	.018	.014	.....	.434	.003	.059	.062	.496	12.5
185	22.1	22.8	0	.383	.....	.013	.....	.396	.....	.....	.063	.459	13.7
			11	.152	.....	.004	.....	.156	.....	.....	.027	.183	14.8
			A	.030	.....	.....	.....	.030	.....	.....	.....	.....	.....
196	32.0	11.2	0	3.417	.068	.102	.034	3.621	.019	.138	.157	3.778	4.2
			11	1.063	.036	.072	.036	1.207	.019	.220	.239	1.446	16.5
			A	1.436	.036	.036	.....	1.508	.008	.121	.129	1.637	7.9
190	31.3	14.8	0	1.466	.314	.140	.140	2.060	.342	.198	.540	2.600	20.8
			11	.595	.018	.036	.....	.649	.008	.190	.198	.847	23.4
			A	.095	.....	.004	.....	.099	.004	.156	.160	.259	61.8
186	27.2	15.7	0	.746	.071	.036	.036	.889	.....	.....	.115	1.004	11.5
			11	.526	.018	.014	.....	.558	.....	.....	.070	.628	11.1
			A	.203	.....	.018	.....	.221	.....	.....	.....	.....	.....
191	29.5	16.6	0	1.708	.018	.035	.....	1.761	.020	.072	.092	1.853	5.0
			11	.886	.018	.025	.....	.929	.011	.174	.185	1.114	16.6
			A	.047	.....	.011	.....	.058	.006	.060	.066	.124	53.2
203	33.1	22.4	0	1.774	.106	.106	.071	2.057	.042	.177	.219	2.276	9.6
			11	.485	.018	.014	.....	.517	.003	.058	.061	.578	10.6
			A	.978	.018	.057	.....	1.053	.003	.093	.096	1.149	8.4
198	40.5	11.4	0	1.363	.035	.069	.069	1.536	.026	.091	.117	1.653	7.1
			11	1.437	.035	.106	.....	1.578	.007	.227	.234	1.812	12.9
			A	1.235	.....	.054	.....	1.289	.003	.085	.088	1.377	6.4
197	39.2	12.6	0	1.480	.140	.105	.140	1.865	.409	.263	.672	2.537	26.5
			11	.871	.018	.036	.....	.925	.006	.144	.150	1.075	14.0
			A	.847	.036	.054	.....	.937	.004	.162	.166	1.103	15.0
188	38.0	13.6	0	1.743	.070	.070	.035	1.918	.107	.080	.187	2.105	8.9
			11	1.182	.071	.071	.....	1.324	.013	.284	.297	1.621	18.3
			A	.464	.....	.037	.....	.501	.....	.....	.....	.....	.....
189	39.2	14.1	0	1.235	.071	.071	.....	1.377	.024	.113	.137	1.514	9.0
			11	.595	.036	.036	.....	.667	.014	.160	.174	.841	20.7
			A	.403	.....	.036	.....	.439	.....	.....	.....	.....	.....
187	35.6	14.5	0	2.505	.173	.208	.311	3.197	2.232	.272	2.504	5.701	43.9
			11	.955	.072	.072	.....	1.099	.006	.069	.075	1.174	6.4
			A	.451	.....	.036	.....	.487	.....	.....	.....	.....	.....

^a In the results 0 indicates samples collected at surface of fuel bed, 11 indicates samples collected 11 inches from fuel bed, and A indicates samples collected at section A of the combustion chamber.

TABLE 11.—Results showing weights of combustible gases, tar, and soot rising from fuel bed, in grams per cubic foot of gas at 60° F. and 30 inches pressure—Continued.

Test No.	Rate of combustion, pounds.	Pounds of air per pound of combustible fired.	Distance of sample from fuel bed.	Combustible gases, grams per cubic foot.					Tar, grams per cubic foot.	Soot, grams per cubic foot.	Total soot and tar, grams per cubic foot.	Total combustible, grams per cubic foot.	Soot and tar, percentage of total combustible.
				Cin CO.	CH ₄ .	H ₂ .	Unsaturated hydrocarbons.	Total gaseous combustible.					
1	2	3	4	5	6	7	8	9	10	11	12	13	14
193	42.0	14.5	0	1.843	.027	.052	.....	1.916	.025	.089	.114	2.030	5.6
			11	1.125	.018	.036	.....	1.179	.006	.143	.149	1.328	11.2
			A	.374	.018	.029	.....	.421	.002	.102	.104	.525	19.8
205	35.2	16.2	0	2.251	.039	.084	.105	2.479	.093	.171	.264	2.743	9.6
			11	1.473	.060	.078	.....	1.611	.027	.272	.299	1.910	15.7
			A	1.083	.018	.025	.....	1.126	.008	.050	.058	1.184	4.9
194	44.2	19.0	0	1.377	.021	.060	.....	1.458	.013	.052	.065	1.523	4.3
			11	.337	.....	.011	.....	.348	.002	.071	.073	.421	17.3
			A	.061	.....	.....	.....	.061	.001	.016	.017	.078	21.8
204	37.9	20.6	0	1.341	.039	.039	.035	1.454	.024	.073	.097	1.551	6.3
			11	.367	.018	.025	.....	.410	.015	.145	.160	.570	28.1
			A	.358	.....	.014	.....	.372	.003	.033	.036	.408	8.8
199	47.1	12.6	0	2.072	.206	.240	.034	2.552	.056	.173	.229	2.781	8.2
			11	.476	.018	.050	.....	.544	.003	.114	.117	.661	17.7
			A	.958	.018	.040	.....	1.016	.003	.061	.064	1.080	5.9
192	45.3	14.8	0	2.543	.038	.083	.....	2.664	.031	.057	.088	2.752	3.2
			11	.703	.018	.029	.....	.750	.005	.111	.116	.806	13.4
			A	.646	.018	.029	.....	.693	.004	.091	.095	.788	12.1
200	50.5	18.3	0	.617	.253	.090	.108	1.068	.079	.052	.131	1.199	10.9
			11	.093	.....	.014	.....	.107	.003	.065	.058	.165	35.2
			A	.493	.018	.025	.....	.536	.002	.041	.043	.579	7.4
201	60.0	15.1	0	1.303	.078	.078	.035	1.494	.032	.112	.144	1.638	8.8
			11	.448	.018	.029	.....	.495	.003	.104	.107	.602	17.8
			A	.559	.018	.029	.....	.606	.002	.054	.056	.662	8.5
202	57.3	16.0	0	1.334	.077	.077	.035	1.523	.008	.056	.064	1.587	4.0
			11	1.036	.039	.050	.....	1.125	.003	.133	.136	1.261	10.8
			A	.310	.018	.018	.....	.346	.002	.045	.047	.393	12.0

The last column of Table 11 shows that of the combustible matter rising from the fuel bed, roughly 12 per cent is in the form of tar and soot. Immediately at the surface of the fuel bed the quantity of tar is large, but decreases rapidly as the gases pass through the combustion space. On the other hand, the soot increases during the first foot of the gas travel. This fact is shown in figure 44, compiled from tests made with Pittsburgh screenings. In the left half of the figure the tests are grouped according to rate of combustion regardless of air supply. In the right half of the figure the tests are grouped according to excess air supply regardless of the rate of combustion. The object of grouping the tests together was to avoid the plotting of too large a number of curves, and also to bring out better the general relation between soot and tar at the different places of sampling. The results of individual tests vary so much among themselves that the general tendency is not easily apparent. Furthermore, it was thought desirable to bring out the effect of the rate of combustion

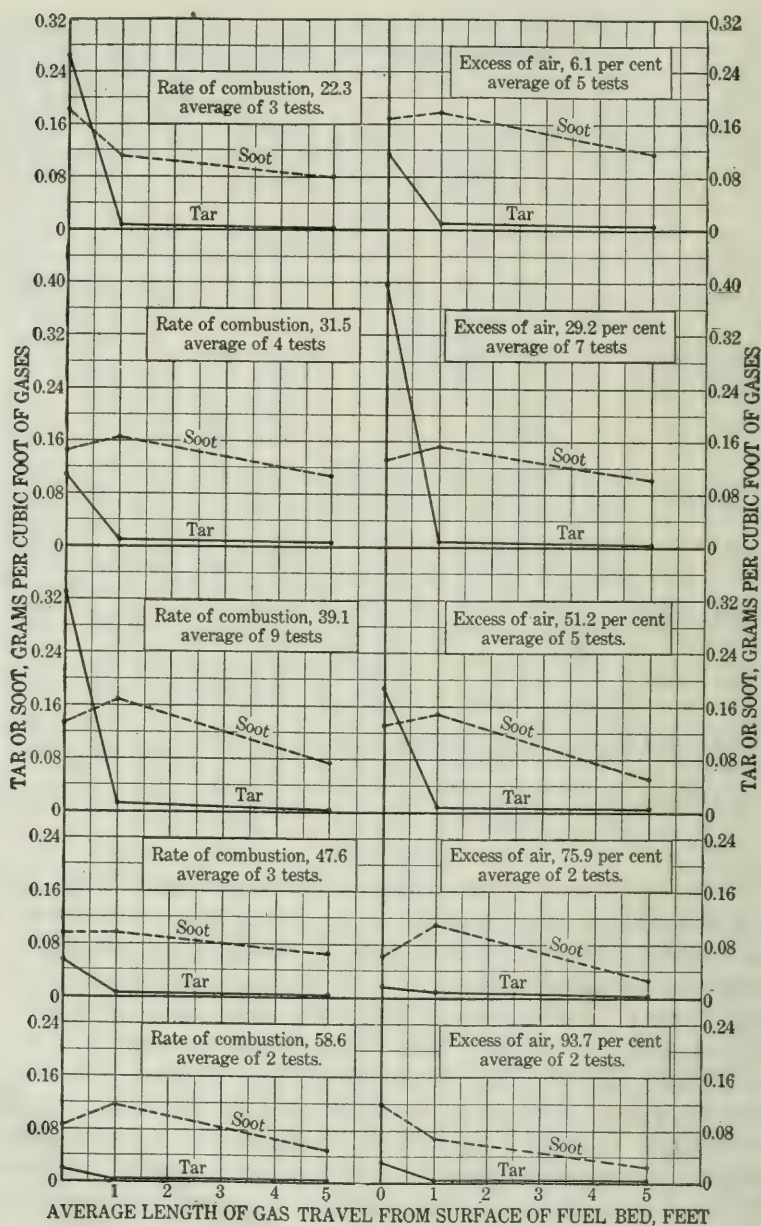


FIGURE 44.—Weight of soot and tar in furnace gases at the surface of, 1 foot from, and an average of 5 feet from the fuel bed. Tests made with Pittsburgh screenings. Tests at left are grouped according to rate of combustion regardless of air supply; those at right are grouped according to air supply regardless of rate of combustion.

and the excess of air on the quantity of tar and soot if any such effect existed. The abscissa in the figure is the length of gas travel from the grate, the ordinates are grams of soot or tar per cubic foot of gas. The weight of tar and soot was obtained from samples collected as described on page 20.

In general an increase in the rate of combustion and in the excess of air is accompanied by a decrease in the quantity of soot, and particularly in the quantity of tar. With all rates of combustion and all excess of air there is a large decrease in the quantity of tar and a moderate increase in the quantity of soot during the first foot of the length of gas travel. This last statement is true of four groups out of five. This decrease in the quantity of tars and increase in the quantity of soot seems to indicate that the volatile matter leaves the fuel bed as heavy hydrocarbons mostly in the form of tars. These tars are decomposed by the high furnace temperature and the absence of oxygen into soot and lighter, mostly gaseous hydrocarbons. The process of the decomposition of the hydrocarbons very likely consists of a number of consecutive reactions, each step of which is accompanied by the deposition of soot and formation of lighter hydrocarbons. This process of decomposition is complicated by the presence of CO_2 , which reacts with soot and combustible gases and is itself reduced to CO . Some of the possible reductions are indicated by the chemical equations on page 124. The decomposition and reduction proceed toward the simple gases CO and H_2 . This view is supported by the fact that samples collected at section A contain only a trace of tars and CH_4 , and a considerable percentage of CO and H_2 . Of course, the process of combustion takes place along with the process of decomposition as far as the supply of oxygen and the mixing makes combustion possible. However, it would be difficult to account for the absence of tarry and gaseous hydrocarbons and the high percentages of CO and H_2 at section A without decomposition and reduction; for, if combustion alone is considered, the simple gases CO and H_2 would burn first, leaving the heavier compounds to be consumed last.

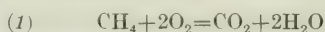
The length of time in which the tars are decomposed into soot and gases is very short. At the rate of combustion of 30 pounds per square foot of grate per hour the gases travel with a velocity of about 10 feet per second. As most of the tars disappear during the first foot of the gas travel from the fuel bed, the time taken for the decomposition of the tar is about one-tenth of a second. This high rate of decomposition is undoubtedly due to the high temperature near the fuel bed, which in the tests was probably not less than 1500°C .

SMOKE IS FORMED AT OR NEAR SURFACE OF THE FUEL BED.

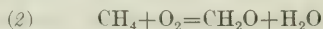
In the light of the preceding discussion it appears that the soot, which is the main constituent of visible smoke, is formed at, or very near, the surface of the fuel bed and not at the place where the furnace gases strike the heating surfaces of the boiler. The heating surfaces merely cool the gases surrounding the soot, thereby preventing its combustion. The formation of soot at the surface of the fuel bed is caused by the high furnace temperature and absence of oxygen. It is possible that if oxygen was present in sufficient quantity at the time of distillation of volatile matter, the heavy hydrocarbons would burn directly to products of complete combustion, CO_2 and H_2O , without first decomposing and depositing soot.

The different processes that may take place according to whether the volatile matter is distilled in the presence of different concentrations of oxygen or in its entire absence can be illustrated by the known behavior of methane at high temperature.

In the presence of a sufficient supply of oxygen methane burns completely, according to the equation:



With insufficient supply of oxygen partial combustion and decomposition of methane take place, which processes are represented by the equations:



In complete absence of oxygen only the process expressed by equation 3 takes place. The carbon precipitates as soot.

With the heavy hydrocarbons the effect of the concentration of oxygen is probably more pronounced because of the great multiplicity of simpler compounds into which they can be decomposed.

After the soot has once been formed it is difficult to burn it in the atmosphere of the furnace. This fact has been observed by many investigators, and some of the early writers on combustion even considered soot as noncombustible. At present no support can be found for this extreme view, as it can be easily shown that soot burns readily if oxygen is furnished in highly concentrated form. For example, if soot is mixed in the right proportion with potassium chlorate and the mixture thrown on a porcelain plate heated to about 500°C ., the soot burns almost instantaneously with a bright flash. Also, if soot is placed in a bomb calorimeter and surrounded with an atmosphere of compressed oxygen, and a source of ignition applied, it burns completely in a very short time.

CAUSES OF THE SLOW BURNING OF SOOT IN A FURNACE.

The soot burns very slowly in the furnace gases because the oxygen is greatly rarified, the gases containing only a few per cent of free oxygen; it burns rapidly in the bomb calorimeter or in mixture with potassium chlorate because it is surrounded with highly concentrated oxygen ready to combine with it.

As a matter of fact, all combustible substances burn slowly in an atmosphere of highly diluted oxygen, but in the case of soot this slowness is much more pronounced. The reason for the very slow combustion of soot in highly diluted oxygen probably lies in its complex molecular structure. It is commonly supposed that a molecule of soot consists of a considerable number of atoms, and that a similarly large number of molecules of oxygen is required to come in contact with the molecule of soot before the latter can combine with the oxygen. The chances of the molecule of soot finding this large number of molecules of oxygen in the furnace gases are small, and hence the slow combustion. Thus assuming the molecule of soot to consist of 12 atoms and represented by the symbol C_{12} , there will be required 12 molecules of oxygen to burn the one of soot. The reaction for the combustion of the soot may be expressed by the formula $C_{12} + 12 O_2 = 12CO_2$. For comparison the reaction for the combustion of CO is given in the following equation, $2 CO + O_2 = 2 CO_2$.

It is easy to understand that the two molecules of CO can find one molecule of oxygen in the furnace gases much more quickly than one molecule of soot can find 12 molecules of oxygen. Therefore simple gases like CO and H_2 burn quickly in the furnace, because they more readily find the small amount of oxygen needed for their combustion; whereas the more complex combustible like soot burns slowly because it can not readily find enough oxygen to effect its combustion.

In general, it may be said that the more complex a molecule of combustible is, the slower is its combustion in any given concentration of oxygen.

At present nothing is known of the molecular structure of soot; the number 12 has been taken only for illustration. There are indications that the actual index number is higher than 12 rather than lower. Experience with burning soft coal shows that if soot is once formed a large percentage remains floating in the gases after all other gaseous combustible has been almost completely burned. In a hand-fired furnace analysis of the flue gases will sometimes show no CO when at the same time black smoke is coming out of the stack. Even a very large combustion space is not an unfailing solution for burning soot, without a large excess of air. In the experimental furnace hav-

ing a long combustion chamber, when a shovelful of coal was spread over the fuel bed the smoke traveled the full length of the combustion chamber and came out of the stack in spite of the apparent whirling motion of the gases and the high temperature in the combustion space.

REASON FOR SUCCESS OF MECHANICAL STOKERS IN BURNING SOFT COAL WITHOUT SMOKE.

It seems that most mechanical stokers are smokeless not because they burn the smoke, but because they burn the coal in such a way that very little soot or smoke is produced. Hand-fired furnaces are smoky because soot is produced in or near the fuel bed, and can not be burned in the limited combustion space of the furnace.

Two of the most important conditions that make mechanical stokers successful in burning smoky coal without smoke probably are: (a) Slow and uniform heating of the coal with the result that a large part of the volatile matter is distilled at low temperature, and (b) distillation of the volatile matter occurs in presence of oxygen.

The great advantage of uniform feeding of coal and air with mechanical stokers is pointed out and discussed in Technical Paper 80^a and is generally known, so that no space need be devoted to it in this discussion.

DISTILLATION OF VOLATILE MATTER AT LOW TEMPERATURE.

Distillation at low temperatures favors the formation of light hydrocarbons of the paraffin series which contain more hydrogen and less carbon than the hydrocarbons of the aromatic group, which are distilled at high temperature. The hydrocarbons of the paraffin series are more stable at high temperatures and on account of their higher hydrogen content are more apt to burn completely without depositing soot than the compounds containing more carbon. It requires one molecule of oxygen to burn completely one atom of carbon, whereas one molecule of oxygen burns completely four atoms of hydrogen. Thus of two compounds having the same number of atoms in a molecule, the one having more hydrogen requires less oxygen for its combustion, and therefore, in the same concentration of oxygen will burn more readily. Instead of the volatile matter being distilled as a heavy hydrocarbon of the composition, say, $C_{15}H_{12}$ and then reduced to $3 CH_4$ by dropping C_{12} , the volatile matter should be distilled as light hydrocarbons, such as CH_4 , and the carbon left in the fuel bed as fixed carbon, in which form it can be burned without any trouble to CO_2 or CO . In the atmosphere above the fuel bed it is

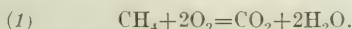
^a Kreisinger, Henry, Hand-firing soft coal under power-plant boilers: Tech. Paper 80, Bureau of Mines, 1915, p. 18.

much easier for a molecule of CH_4 to find two molecules of oxygen for its combustion than it is for a molecule of $\text{C}_{15}\text{H}_{12}$ to find its requirement of 18 molecules. The general formulas of the more common hydrocarbon compounds are given in the table following:

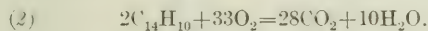
Some of the more common hydrocarbons arranged in order of decreasing contents of hydrogen.

	Compound.	Formula.
Unsaturated hydrocarbons.....	{ Paraffins.....	$\text{C}_n\text{H}_{2n+2}$
	{ Olefins (ethylene).....	C_nH_{2n}
	{ Acetylene.....	$\text{C}_n\text{H}_{2n-2}$
	{ Benzene.....	$\text{C}_n\text{H}_{2n-6}$
Aromatic hydrocarbons.....	{ Naphthaline.....	$\text{C}_n\text{H}_{2n-12}$
	{ Anthracine.....	$\text{C}_n\text{H}_{2n-18}$

In the above table attention is called to the decrease of the hydrogen contents as we pass from paraffins through the unsaturated and aromatic hydrocarbons to the anthracine. If these formulas be considered as purely arithmetical formulas it is plain that in the anthracines the n can not be less than 10, whereas in the case of paraffins n is as low as 1, which gives the formula of methane, CH_4 , which is the lightest hydrocarbon and burns more readily than any other carbon-hydrogen compound. A molecule of methane needs for its complete combustion two molecules of oxygen, as shown by equation 1 following:



On the other hand, the lightest anthracine imaginable would be C_{10}H_2 , which would take not less than 11 oxygen molecules. The lightest anthracine known is $\text{C}_{14}\text{H}_{10}$, which burns according to equation 2.



That is, to burn two molecules of anthracine would require 33 molecules of oxygen.

The preceding discussion shows the advantage of distilling volatile matter at low temperatures producing mostly paraffins or other hydrocarbons having light molecules. The furnace should be so designed that the distillation takes place at low temperature. After the volatile matter is distilled air should be added and the mixture then passed through a hot chamber.

DISTILLATION OF THE VOLATILE MATTER IN PRESENCE OF OXYGEN.

The principal methods of feeding coal and air in commercial furnaces are indicated in figure 45. In the hand-fired furnace (A) the air first comes in contact with the partly burned coal at the bottom of the fuel bed containing no volatile matter. Before the air reaches the distillation zone at the top of the fuel bed all the oxygen is practically used, so that the distillation occurs in absence of oxygen.

The heat is imparted to the freshly fired coal by conduction and by radiation from the hot fuel bed below, by convection from the hot gases passing through it, and by radiation from the hot furnace walls and fire-brick arches, if there happen to be any. Therefore the heating of the fresh coal is very rapid. In the side-feed types of stoker

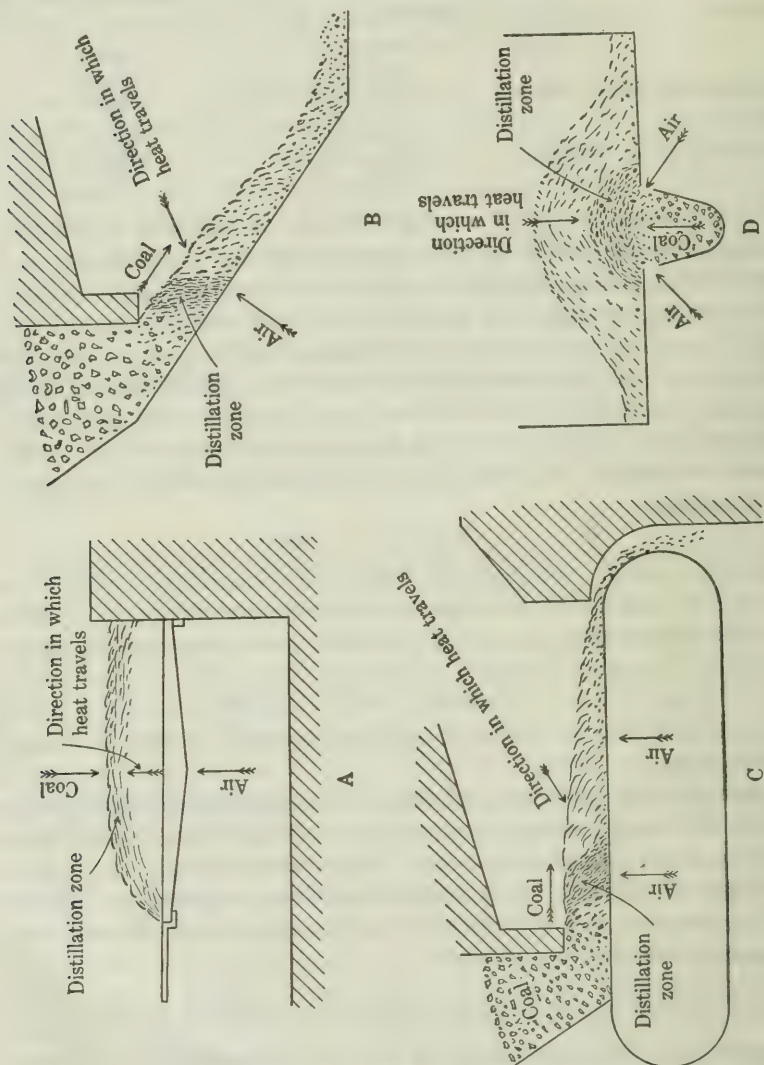


FIGURE 45.—Principal methods of feeding coal and air in commercial furnaces. *A*, hand fired; *B*, side feed by gravity and agitation of grate bars; *C*, side feed with chain grates; *D*, underfeed. The arrows indicate direction of feeding coal and air, and also the direction in which heat travels and is imparted to the fresh coal. The distillation zone is indicated by dark shading.

(*B* and *C*) the distillation zone extends the full thickness of the fuel bed, and the air comes in contact with the fresh coal before the oxygen is all used, so that the distillation occurs in an oxidizing atmosphere. The heat is imparted to the fresh coal by conduction and radiation from the hot coal in front, and by radiation from the hot

furnace walls and arches. No heat is imparted by convection from the air passing through. Therefore the heating is slower than in a hand-fired furnace. In the underfeed type of stoker (D) the air and coal is fed into the furnace in the same direction, so that the distillation occurs in air with its content of oxygen previously undiminished by combustion. The same is true in the burning of pulverized coal. In the underfeed stoker the heating of the coal takes place only by conduction and radiation from the upper layers of the fuel bed, against the convection from the stream of cold air. The heating is therefore slow.

A study of figure 45 will show that in most of the common types of mechanical stokers the distillation of volatile matter occurs in the presence of oxygen, whereas in hand-fired furnaces the distillation takes place in almost entire absence of oxygen, all of the latter being consumed as it passes through the fuel bed.^a Even if there should be some tendency to decomposition with the mechanical stokers, the presence of large percentages of oxygen at the point of distillation makes it possible for the hydrocarbons to react with oxygen before the deposition of carbon can really take place.

High temperatures such as exist in boiler furnaces and absence of oxygen promote the decomposition of all hydrocarbons, including methane, the lightest of the paraffin series, one of the products of decomposition being soot.

When methane is burned with insufficient air supply, it burns with a yellow flame and deposits soot. Therefore, natural gas, which consists mostly of methane, should be burned with some excess of air and with provision for obtaining a good burning mixture; otherwise soot will be deposited and gas will be wasted, owing to incomplete combustion. In this respect natural gas differs greatly from producer gas, the latter consisting mostly of carbon monoxide, which does not readily decompose. An instance showing the difference in the behavior of the two gases came recently to the writer's attention. A porcelain-ware manufacturer used producer gas for burning his product. The kiln in which the burning was done had one chamber for the ware and another surrounding it for the burning of the gas, the two chambers being separated by a partition of a highly refractory material. The products of combustion did not come in direct contact with the ware, so that the heat had to be transmitted through the partition. The gas to be burned was introduced into the combustion chamber all at one point, but to have the temperature more uniform throughout the chamber, air was admitted at several points along the path of the combustion gases. Thus the process of combustion was distributed over a large space and nearly uniform temperature was obtained.

^a Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., *Combustion in the fuel bed of hand-fired furnaces*, Tech. Paper 137, Bureau of Mines, 1916, 76 pp.

This method of obtaining uniform temperature worked splendidly with producer gas. The owner was persuaded to change to natural gas, and when he tried the same method of burning it as he used with the producer gas, he found that a layer of soot was deposited on the partition, preventing to a large degree the transfer of heat to the ware. At the same time a large part of the heat value of the carbon in the methane was never developed, owing to deposition as soot. He used entirely too much gas and obtained unsatisfactory results.

The amount of air admitted at the point where the gas was introduced, which was by design far from enough for complete combustion, was sufficient to heat the methane to a temperature at which it decomposed into carbon, hydrogen, and some carbon monoxide. A large part of the carbon settled on the surface as soot while the hydrogen and carbon monoxide were burned with the air added along the path of the gases.

When changing to natural gas the method of burning it should also have been changed. The gas should have been introduced into the kiln in a number of small jets evenly distributed over the area where uniform temperature was desired. With each gas jet a sufficient amount of air should have been supplied to insure complete combustion and thus prevent the deposition of soot.

This affords a very instructive example of what happens when the hydrocarbons are burned with insufficient air supply. By air supply is meant the air available for combustion at the point where the hydrocarbons are heated or generated in the furnace; any air that is added later along their path, is added too late, because the hydrocarbons are already decomposed by heat into soot and more stable gases. To insure rapidity and completeness of combustion in burning soft coal the distillation of volatile matter, which consists mainly of hydrocarbons, should take place in the presence of oxygen in order to prevent the formation of soot. In most mechanical stokers this condition is more or less closely approached; in hand-fired furnaces it is not. As shown in Technical Paper 137^a no oxygen penetrates to the distillation zone in hand-fired furnaces, hence the decomposition of the hydrocarbons in presence of CO_2 into soot, CO and H_2 .

The two conditions for smokeless combustion with mechanical stokers could be perhaps applied to gas producers to eliminate soot and tar from the producer gas; that is, to distill the volatile matter at low temperatures and in strongly oxidizing atmospheres so that the hydrocarbons burn to the products of complete combustion, CO_2 and H_2O ; then by passing these products through a bed of hot coke to decompose them into CO and H_2 . This process of gasification is similar to that which takes place in the underfeed type of mechanical stoker.

^a Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., combustion in the fuel bed of hand-fired furnaces: Tech. Paper 137, Bureau of Mines, 1915, 76 pp.

STABILITY OF HYDROCARBONS.

Hydrocarbons are decomposed or cracked by heat. Carbon and hydrogen are the ultimate products when cracking is carried to the end. The decomposition is a complicated process, the exact mechanism of which is not known, but it is governed by the laws of physical chemistry. Equilibrium conditions determine the extent to which cracking occurs, and the values of the equilibrium constant depend, among other factors, upon the temperature and pressure. High temperature favors cracking because most of the reactions take place with absorption of heat. The influence of pressure need not be considered here as the pressure in boiler furnaces is always very nearly atmospheric.

Mayer and Altmayer investigated the stability of methane and found the following percentages were stable in the presence of hydrogen.

Percentage of methane in equilibrium with hydrogen and carbon at various temperatures.^a

Temperature, C.....	250°	450°	550°	750°	850°
CH ₄ , per cent.....	98.79	76.80	46.69	6.08	1.59

The reaction is represented by the expression $\text{CH}_4 = \text{C} + 2 \text{H}_2$. At 850° C. and atmospheric pressure 1.59 per cent of methane is in equilibrium with hydrogen whose partial pressure is then 0.9841 atmospheres. As the partial pressure of the hydrogen decreases the equilibrium pressure of methane decreases also. The partial pressure of hydrogen in the furnace is small and the temperature much higher than 850° C., therefore it is evident that only a very small percentage of methane can exist in equilibrium in a boiler furnace. This deduction is confirmed by the fact that only small traces of CH₄ were found in the long combustion chamber, except immediately at the surface of the fuel bed before it had had sufficient time to decompose.

Such equilibrium conditions as given for methane are not available for other hydrocarbons present in furnace gases, but experimental data show that methane is much more stable than ethylene or ethane. In general, the simple hydrocarbons are more stable than those of higher molecular weight.

Equilibrium conditions, although they tell the extent to which cracking will proceed if allowed sufficient time, do not give any information as to the velocity of decomposition, which is important in furnace and gas-producer practice.

The process of decomposition of hydrocarbons is probably a gradual dehydrogenation. Compounds of higher molecular weight are decomposed into compounds of lower molecular weight with liberation of hydrogen or a simple hydrocarbon. These intermediate

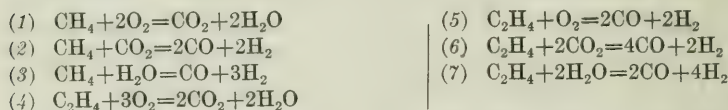
^a Haber, F., *Thermodynamics of technical gas reactions*. Translation by Lamb., A. B., 1908, p. 345.

compounds are in turn decomposed. Some of the products, particularly the carbon, may polymerize to form compounds of higher molecular weight. The decomposition does not follow any single path, but is influenced by the temperature and pressure. The ultimate products are carbon and hydrogen.

Black smoke is the result of this decomposition of hydrocarbons driven from coal as volatile matter. The black part of smoke consists almost entirely of finely divided carbon. Analyses of the solid portion, or soot, show it to be nearly pure carbon, with a little tar and ash.

The temperatures in a boiler furnace are much higher than those given in the preceding table and therefore more rapid decomposition would be expected. Gases collected above the fuel bed of the furnace described in this bulletin contained only a small percentage of methane. At an average distance of 5 feet from the fuel bed one or two tenths of a per cent of methane was frequently found, which is about the limit of accuracy of the methods of gas analysis used. Unsaturated hydrocarbons which were found in the gas samples collected at the surface of the fuel bed had entirely disappeared at an average distance of 5 feet, and in most cases none were found 11 inches above the fuel bed.

Although the direct decomposition of hydrocarbons by heat may be a slow process, methane especially being decomposed slowly, their disappearance in the furnace may be quickened by their reaction with oxygen or some of the products of combustion such as CO_2 and H_2O . The following equations indicate some of the reactions that may occur:



Only when combustion is very poor, owing to inadequate space above the fuel bed and rapid cooling of the gases, are hydrocarbons likely to be found in flue gas.

What has been said regarding the decomposition of hydrocarbon gases applies also to the cracking of tar. Tar is a complex substance containing hydrocarbons of high molecular weight, which are liquid or solid at ordinary temperature.

Lunge^b gives a list of over 200 compounds which have been found or may reasonably be presumed to exist in coal tar. In contrast with gaseous hydrocarbons those which are liquid and solid contain a much larger number of carbon atoms in the molecule and consequently deposit more carbon when they are cracked.

^b Lunge, G., Coal tar and ammonia, 4th ed., 1909, p. 160.

Tar exists in the furnace in the form of vapor, an ideal condition for cracking. The small globules present a large surface for absorption of heat from the gases and hot furnace walls, and are quickly heated to a high temperature, which favors the formation of carbon.

On account of the complex nature of tar a great many reactions are involved in its decomposition. In general, the cracking is similar to that of hydrocarbon gases but many more compounds are involved and the result is a very complicated equilibrium among a large number of hydrocarbons. Very little experimental data are available on equilibrium and the velocity of these reactions; however, the high temperature in the furnace and the fact that the tar is in a state of fine subdivision favor rapid cracking and the formation of large amounts of carbon. This view is supported by the results shown in figure 44.

Table 11 also shows that the greatest amount of tar is found with a larger proportion of soot. The content of tar in the gases decreases rapidly as the distance from the fuel bed increases; at an average distance of 5 feet the tar has very nearly disappeared.

The velocity of combustion of hydrocarbons is faster than velocity of decomposition; therefore, combustion will take precedence over decomposition. For this reason air supplied over the fuel bed should be admitted as near to the surface of the bed as possible and mixed with the hydrocarbons, so that they will be burned before they are decomposed by heat and form smoke, which is difficult to burn in the rarified oxygen of the furnace.

PHYSICAL CHEMISTRY OF COMBUSTION OVER THE FUEL BED.

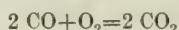
Combustion over the fuel bed is a chemical reaction between gaseous oxygen on the one hand and gaseous, liquid, and solid combustible, which rises from the fuel bed, on the other hand. The gaseous and liquid combustible results from gasification of fixed carbon on the grate and distillation of volatile matter. The solid combustible consists chiefly of finely divided carbon, known as soot, which is produced by decomposition of volatile matter. Also particles of coal are carried along with the current of gases. To burn these gaseous, liquid, and solid combustible materials oxygen must be supplied by admitting air over the fuel bed. The velocity and completeness of combustion are influenced by concentration, mixing, temperature, and time of contact of oxygen and combustible, and therefore a knowledge of their effects is important.

CONCENTRATION OR MASS ACTION.

According to the kinetic theory, gases consist of freely moving molecules. The contacts or collisions among molecules of different nature produce chemical action. Therefore for complete combustion

to take place in the mixture of gases, each molecule of the combustible must come in contact with the number of oxygen molecules required to burn it. The concentration or number of molecules of combustible gas and oxygen in a unit volume will influence the number of collisions taking place. According to the law of mass action, the velocity of a chemical reaction in the combustion process is proportional to the products of the concentrations of the oxygen and the combustible substances; that is, if one molecule of substance A reacts with one molecule of substance B the velocity of the reaction at any moment is proportional to the product of the number of molecules of A and B present in unit volume. If several molecules of one substance are taking part in the reaction, the concentration of that substance must be raised to the corresponding power. Thus if one molecule of substance A reacts with two molecules of substance C the velocity of the reaction will be proportional to the number of molecules of substance A in unit volume multiplied by the square of the number of molecules of substance C in unit volume. Thus it can be said that the velocity of a chemical reaction increases when the concentration of the reacting substances increases.

In the combustion of coal the law of mass action manifests itself by the fact that in boiler furnaces a considerable excess of air above the theoretical requirement is necessary to insure complete combustion within the furnace. If the air supply is reduced to nearly the theoretical amount the combustion is so slow that a large percentage of the gases may leave the furnace before they are burned. With low excess of air the time required to complete the combustion is long and the combustion space must be large. This fact is shown by the positions of the curves representing the different excesses of air in figures 29 and 30. In combining with the oxygen, carbon monoxide forms carbon dioxide according to the following reaction:



It can be easily seen that if there are two molecules of carbon monoxide and 10 molecules of oxygen in a unit volume, the chances of one molecule of oxygen meeting two molecules of carbon monoxide are greater than if there were only two molecules of oxygen present. When oxygen in a mixture of air and combustible in the furnace unites with carbon monoxide, this oxygen is no longer available for oxidation of the remaining combustible gas. Furthermore, the molecules of oxygen and combustible gas removed are replaced by the products of combustion which dilute the mixture, and the remaining molecules of oxygen and combustible gas come in contact less frequently. As combustion proceeds the concentration of the oxygen and combustible gas becomes less and less and the velocity of combination becomes slower and slower.

When dealing with the law of mass action the concentration of the chemical substances is expressed in gram molecular units. The volumetric weights of gases are directly proportional to their molecular weights, because equal volumes of all gases at the same temperature and pressure contain the same number of molecules. Therefore, with gases analyzed volumetrically all that is necessary is to substitute the volumetric percentages in the equation corresponding to the particular reaction and obtain the relative rate of combustion, assuming the same temperature and pressure in each case. For example, two samples of gas collected at section C of the combustion chamber showed the following percentages of O_2 and CO, the temperature in each case being $2400^\circ F.$:

$$(1) \quad O_2=4.0 \text{ per cent, CO}=0.5 \text{ per cent.}$$

$$(2) \quad O_2=7.0 \text{ per cent, CO}=0.4 \text{ per cent.}$$

The rest of each sample was nitrogen, carbon dioxide, and water vapor. What was the relative velocity of combustion of CO at each of the two sections? The equation representing the reaction between oxygen and carbon monoxide is $2 CO + O_2 = 2 CO_2$. At a temperature of $2400^\circ F.$ the dissociation of CO_2 is only about 0.2 per cent.

Therefore one may say with close accuracy that the reaction at this temperature is not reversible but proceeds to a finish from left to right. The relative rates of combustion in the two cases are:

$$(1) \quad 4.0 \times 0.5^2 = 1.0.$$

$$(2) \quad 7.0 \times 0.4^2 = 1.12.$$

The velocity of combustion in the second case is greater on account of higher concentration of CO.

Another example is given in the following: Assume that the gas mixture in the long combustion chamber contains at section A 10 per cent CO and 9 per cent O_2 , and at section C 0.6 per cent CO and 4.0 per cent O_2 , what are the relative rates of combustion of CO in each case? The rate of combustion of CO at section A is $9 \times 10^2 = 900$, whereas the rate of combustion of CO at section C is $4 \times 0.6^2 = 1.62$. These figures show that the rate of combustion of CO is over 500 times as fast at section A as it is at section C.

The following table gives the CO and O_2 content in the furnace gases sampled in test 187 at four sections of the path of gases, and the corresponding relative velocities of combustion calculated as in the two preceding examples. The four sections are: The surface of the fuel bed, 11 inches from the surface of fuel bed, section A, and section C. The calculated relative velocities are shown in figure 13 (p. 54) by the dotted curve which is nearly parallel to the curve of total combustible. With this dotted curve the scale at the right of the figure should be used.

^a Nernst, W., and Wartenberg, H. von, Ueber die dissociation der Kohlensäuren: Ztschr. Phys. Chem., Bd. 56, 1906, p. 548.

Content of CO and O₂ in furnace gases of test 187 and the corresponding relative velocity of combustion of CO.

Point of sampling.	CO in gases.	O ₂ in gases.	Relative velocity of combustion of CO.
	<i>Pet cent.</i>	<i>Per cent.</i>	
At surface of fuel bed.....	16.4	1.3	350
11 inches from fuel bed.....	6.4	2.9	119
Section A.....	3.1	3.2	31
Section C.....	0.4	4.9	0.78

When several combustible gases with more complex molecular structure are present, the calculation of velocities of reactions becomes complicated by reactions among the combustible gases themselves. The reactions are interrelated and can not be considered independently, but with simple gases such as in CO and H₂ less complication from side reactions is to be feared than with complex substances. At any rate the law of mass action is a valuable guide in such problems, and if the facts do not fit proved formulas well, usually too little theory has been applied, and some refining corollaries must be added.

With more than one combustible gas of simple molecular structure, the combined velocity of combustion can be obtained by adding together their individual velocities. However, care must be taken not to add these velocities without first multiplying each by the proper constant for that particular gas. At present not all of these constants are known, therefore it is not feasible to formulate an expression for the comparative total velocities of combustion of all the constituents taken together at several points along a flame.

Thus far the law of mass action as applied to the combustion of gases has been considered. This law is also a valuable guide in studying the combustion of the small particles of solid carbon, or soot, and the tar vapors, which are present as small globules. The mass, or concentration, of the solid carbon or the tar globule is very large compared with that of gaseous oxygen, so that the velocity of reaction depends on the rate with which the oxygen comes in contact with the surface of hot particles of carbon or tar globules. The faster oxygen is supplied to the surface, the higher is the velocity of the reaction. The rate at which oxygen is supplied to the surface of these carbon particles and tar globules is proportional to the percentage of the oxygen in the furnace gases.

The particles of carbon and the tar globules are so small that unless they are constantly agitated they tend to adopt the motion of the surrounding gas and consequently there is little or no relative velocity between them and the gas, to scrub off the layer of products of combustion and allow oxygen to act upon the surface of the

particles. Removal of the products of combustion from the surface and the supplying of free oxygen must be largely accomplished by natural diffusion, which is a slow process. This is one of the reasons why the combustion of soot and tar vapor is slow.

MIXING OF AIR AND GASES.

A chemical action can take place only when the reacting substances are brought into contact; this is true of gases as well as of liquids and solids. Thus, in the combustion of gases, which is a chemical process, there must be contact between the molecules of the combustible gas and of the oxygen before there can be combustion. This contact takes place most readily when the gases and the air containing the oxygen form a uniform mixture. The preceding calculations of the velocities of combustion according to the law of mass action are directly applicable only to uniform mixtures of the combustible gas and the air containing the oxygen. If they do not form a uniform mixture more time is required for the oxygen to come in contact with the combustible substances and the velocity of combustion will not be according to the law of mass action, but will be limited to the rate of mixing.

For example, if a cubic foot of CO and a cubic foot of O₂ were mixed thoroughly and the mixture placed in a hot furnace, combustion would proceed according to the law of mass action and would be rapid. If, on the other hand, the cubic foot of CO and the cubic foot of O₂ were placed in the hot furnace in such a way that the cubes would be in contact on one side only, combustion would take place only along the common surface of contact of the two gases and not within the cubes. The combustion would be slow, its velocity being limited to the rate at which molecules of CO and O₂ were coming to the common surface of contact. If this movement of molecules is left entirely to the natural diffusion of gases, the rate of the reaction would be slow—much slower than in a uniform mixture because natural diffusion of CO and O₂ is much slower than their velocity of combustion in uniform mixtures. If, however, the two cubic feet of CO and O₂ were violently stirred, the rate of CO coming in contact with O₂, or their mixing, would be rapid, and the velocity of combustion would approach that of uniform mixture, according to the law of mass action.

In commercial furnaces the combustible gases and the oxygen seldom form a perfectly uniform mixture, hence the rate of burning is not altogether controlled by the law of mass action but largely by the rate of mixing. This is especially true of the furnace gases near the surface of the fuel bed. The combustible gases leave the fuel bed in a solid stream containing little or no free oxygen. To this stream of combustible gas, air is added through the fire door or other special

openings. If this air is added in comparatively large streams that are not agitated, the streams of combustible gases and the air may flow through the furnace for some distance in more or less stratified streams, and the combustion take place only along the surfaces of contact and be slow. Such combustion makes itself evident as long flames. When the air is added in a large number of small streams, or when the large streams are agitated so that they break into a large number of small streams, the surface of contact is large and the combustion is rapid, approaching the velocity of combustion of a uniform mixture. Such combustion is manifested by short and hot flames.

Evidently, the length of the flame depends not only on the nature of the combustible, the excess of air, and the rate of firing, but also to a large degree on the rate of mixing of the combustible gases with the oxygen of the air. It has been shown in connection with Tables 8, 9, and 10 that the tendency of the gases is to flow in parallel streams even when the air was introduced into the furnace in many small streams through the tuyères of the furnace.

Mixing effects apply equally well to the combustion of soot and tar. The velocity at which these burn in the furnace depends upon the rate at which oxygen is supplied to their surfaces and the products of combustion are removed. Tar and soot particles are heavier than the gases surrounding them and change the direction of their motion less readily, therefore mixing creates a relative velocity between them and the gases. This relative velocity tends to scrub from their surfaces the products of combustion and to replace these with free oxygen.

Probably mixing has a further important effect on the combustion of the tar. A large part of the tar in the furnace is small globules, somewhat like visible steam rising from boiling water. When air is absent heating breaks up these globules of tar in various ways, the ultimate products being hydrogen and the finely divided solid carbon known as soot. In the presence of air it is quite likely that the reactions are different, oxygen taking part, and giving as final products CO_2 and H_2O with very little or no soot. This phase of combustion is discussed on pages 118 to 122.

A bunsen burner can be used to show how mixing air with a flame affects combustion. When the air supply is turned off the flame from a bunsen burner is luminous. Its luminosity is due to incandescent particles of solid carbon resulting from the decomposition of hydrocarbons in the gas. The interior of the flame contains no oxygen to burn the hydrocarbons, and they are decomposed by heat into hydrogen and carbon.

When air is mixed with the gas as it enters the burner, the flame is nonluminous and has a well-defined inner cone. In this inner cone the oxygen of the air combines with hydrocarbons of the gas, pro-

ducing H_2 and CO, which burn on the outer envelope of the flame. The reactions in the presence of oxygen produce gases that are easily burned, whereas the carbon produced in the absence of air is difficult to burn. Similarly, air mixed with volatile matter in the furnace before the tar is decomposed by heat may produce a larger proportion of combustible in the form of gas and less in the form of carbon.

Obviously, mixing is an important factor in combustion. Merely an excess of air in the furnace is not enough; the air must be supplied as near to the surface of the fuel bed as practicable, and be thoroughly mixed with the combustible matter in order that the combustion may be completed in a short time and a small combustion space made effective.

The importance of mixing was pointed out about 10 years ago by Breckenridge,^a as follows:

On page 61 is given a calculation based on actual data obtained, and the conclusion is reached that the velocity of combustion decreases enormously from the surface of the fire to the rear of the combustion chamber, where it is relatively very small, the practical application is that little is to be gained by adding further length of smooth combustion chamber, which would be commercially as poor an investment of capital as to add to the length of a Corliss engine cylinder and stroke; we must resort to thorough mixing.

Breckenridge^b further states:

It will be probably found on attempting this reduction of dimensions and cost that the limit will be not in the boiler as such, but in the combustion chamber. Burning a large amount of coal in a small grate area is largely a question of draft and continual riddance of ash, but the rate of travel of gases through a combustion chamber is dependent, practically, only on the amount of carbon burned per unit of time, the rate being about the same no matter what the air supply per pound of carbon. As combustion chambers are now constructed for western coals they are too small, but "small" is a word not to be understood in this connection as referring to volume or length alone. By a "small combustion chamber" is meant a chamber in which either the time spent by the gas in traveling from the front to the rear of the boiler is short or the mixing devices are inefficient or absent. In the discussion of mass action it was stated that mere length of combustion chamber counts for little—that **mixing is what counts**—and thus there is a possibility of enormously increasing the efficiency of a combustion chamber as a burner of volatile matter. Efforts in completing a steam generating outfit of small dimensions must be largely concerned with the construction of a combustion chamber containing many gas-mixing appliances.

Mixing can be obtained by using special fire-brick structures in the combustion space, such as piers on the bridge wall or in the combustion space beyond the bridge wall, deflecting arches, and wing walls. Such structures change the direction of flow of the gases and create a relative velocity between tars and soot and the air, and between different streams of gases, thus tending to produce a uniform mixture. The chief objection to such structures seems to be

^a Breckenridge, L. P., Study of four hundred steaming tests: Bull. 325, U. S. Geol. Survey, 1907, p. 171.

^b Breckenridge, L. P., Work cited, p. 178.

their lack of durability. In these days of high furnace temperatures, the main condition of high efficiency, such structures are destroyed in a comparatively short time and their maintenance entails considerable expense.

Another method of mixing the gases and air is to introduce the air at high velocity either by means of steam jets or by forcing the air over the fuel bed with a blower. The jets of steam or of air cause a whirling motion over the fuel bed and tend to produce a uniform mixture. The best results are obtained when the air is admitted in a large number of small streams. When steam jets are used it should be remembered that it is not the quantity of steam but high-velocity streams of air that are wanted in the furnace. The steam jets are also inefficient as air movers.

TEMPERATURE IN COMBUSTION CHAMBER.

The velocity of chemical reaction increases with rise in temperature. At ordinary atmospheric temperatures the oxidation of carbon monoxide and hydrogen proceeds so slowly that the velocity of reaction can not be measured. At high temperatures and with thorough mixing, oxidation takes place rapidly; that is, the gases burn.

Experimental work has shown that at ordinary furnace temperatures the velocity is about doubled when the temperature is increased 10°C . At high temperatures the increase is less, but may be said to be of this order of magnitude. The velocity of reaction increases in geometric progression, whereas temperature increases in arithmetical progression. This means that if a reaction has a velocity of 1 at $1,000^{\circ}\text{C}$., assuming that the velocity is doubled for each increase of 10°C ., then at $1,100^{\circ}\text{C}$. the reaction has a velocity of 1,024, and at $1,200^{\circ}\text{C}$. the velocity is 1,048,576.

The temperature in a boiler furnace is about $1,400^{\circ}\text{C}$. At this temperature oxygen reacts with the combustible material to be burned very rapidly, but proper conditions for reaction must be provided.

When coal is burned carbon dioxide and water are the final products of complete combustion. The extent to which they are dissociated depends upon the temperature in the furnace and determines the limit of completeness of combustion.

Nernst and Wartenberg^a studied the reaction $2\text{CO}_2 \rightleftharpoons 2\text{CO} + \text{O}_2$ and found that the dissociation of CO_2 at one atmosphere at $1,323^{\circ}\text{C}$. was 0.104 per cent, at $1,423^{\circ}\text{C}$., 0.242 per cent, and at $1,523^{\circ}\text{C}$., 0.507 per cent.

Löwenstein^b studied the reaction for the formation of water, $2\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2 + \text{O}_2$, and found that the dissociation at one atmos-

^a Haber, F., *Thermodynamics of technical gas reactions*, 1908, p. 323.

^b Haber, F., *Work cited*, p. 332.

phere at $1,432^{\circ}\text{C}$. was 0.102 per cent, at $1,510^{\circ}\text{C}$., 0.182 per cent, and at $1,590^{\circ}\text{C}$., 0.354 per cent.

As shown by the preceding data, at furnace temperatures carbon dioxide and water vapor are only slightly dissociated. Therefore it is evident that at equilibrium very little carbon monoxide and hydrogen can exist in the furnace. The combustion to carbon dioxide and water will be complete if given time enough.

TIME OF CONTACT.

If reactions are allowed sufficient time they will proceed to equilibrium. The length of time required depends upon the velocity of reaction; the slower the velocity the greater is the time necessary to reach equilibrium. As stated previously, CO_2 and H_2O are only slightly dissociated at furnace temperatures, and therefore when equilibrium is reached combustion is practically complete.

Equilibrium conditions determine what products are formed and the amounts. They do not give information on velocity of reaction. At present the velocity coefficients of the reactions that occur in the furnace are not all known definitely; therefore it is not possible to obtain an expression for their relative velocities. However, it is known that some of the combustible gases formed in the fuel bed will burn almost instantaneously at temperatures below those in the furnace when mixed with oxygen in proper proportions to make an explosion. An explosion is simply very rapid combustion, and therefore it can be said the velocity of combustion is sufficient to burn the gases in a very short time if they form a uniform mixture with a sufficient amount of air. In most furnaces that are in use the time required for complete combustion is not determined by the velocity of chemical reaction but by the rate of mixing.

One must remember that combustion of coal is not a simple oxidation of carbon and hydrogen to CO_2 and H_2O , but is a complex process. The volatile matter from heated coal contains tar, saturated and unsaturated hydrocarbons, carbon monoxide, and hydrogen, all of which must be burned in the space above the fuel bed. These materials all react among themselves and with the products of their combustion. Each reaction exerts its influence upon the others and can not be considered separately. The high temperature in the furnace favors the formation of simpler compounds so that the final products to be burned are largely soot, CO , and H_2 .

When other factors remain constant the velocity of combustion and the time of contact necessary for the completion of the reaction are closely related. The time of contact may be considered to be the length of time during which the combustible and the air supplied over fuel bed remain in the furnace. If the velocity is slow a long time of contact is required for complete combustion and a large

combustion space must be provided in order that the gases may be burned before they pass out of the furnace and are cooled. The rate of burning the coal and the size of combustion space determine the length of time the gases remain in the furnace. As the size of combustion space with a given furnace setting is constant the time the gases remain in the furnace is proportional to the rate of combustion. With high rates of combustion a larger volume of gases is produced and a larger volume of air must be supplied to burn it than with low rates of combustion. The larger volume of the mixture passes through the combustion space more rapidly; therefore the length of time the mixture stays in the furnace or the time of contact is shorter. The combustion space should be large enough so that the gases and the oxygen in the air supplied remain in contact long enough to burn the gases completely when the furnace is operated at its maximum capacity.

Concentration, mixing, temperature, and time of contact are interrelated and each of these factors is essential for good combustion. Consideration of these four factors indicate the conditions necessary to obtain good results. These conditions are: (1) Enough air; (2) air and the combustible gases thoroughly mixed; (3) a furnace temperature above the ignition point of the gases; (4) enough time for combustion to be complete.

In practice an excess of air is required, but the amount of excess air can be small if the mixing is thorough. Mixing is probably the most important single factor and the one most frequently responsible for poor combustion. A large excess of air and high temperature will do no good unless the air is mixed with the furnace gases and the oxygen and combustible gas brought into contact.

FUTURE METHODS OF USING BITUMINOUS COAL.

Difficulty in burning bituminous coal in industrial furnaces is due almost entirely to the volatile matter, because this leaves the fuel bed as gases and tars and must be burned in the combustion space of the furnace. Unless enough air is introduced immediately at the surface of the fuel bed and thoroughly mixed with the volatile combustible, the tars and the more complex combustible gases are quickly decomposed or "cracked" into soot and simple gases. The soot thus formed is difficult to burn in the rarified furnace atmosphere and is apt to pass out of the furnace as black smoke, particularly if the furnace is hand fired. To prevent smoke and its accompanying heat losses, a considerable excess of air must be used and the furnace must have a large combustion space containing gas-mixing devices. The fixed carbon is easy to burn because it stays on the grate. It burns partly to CO_2 , and partly to CO , which in turn can be burned to CO_2 with the additional air introduced above the

fuel bed. Practically complete combustion of CO is easily obtained because of its simple molecular structure.

During the past 15 or 20 years considerable attention has been given to designing of furnaces that would burn bituminous coals without producing smoke. Campaigns have been conducted to educate the fireman and induce him to use proper methods of firing the coal so as to produce the least amount of smoke. Large cities passed smoke ordinances aiming to reduce the smoke by encouraging or forcing the coal user to install apparatus that would burn coal smokelessly. These methods of attacking the problem have had much success but the production of unnecessary smoke continues. A large part of this smoke is made in a way that can not be easily controlled, even with good intentions on the part of the offenders.

In view of what is known of the chemistry of the various kinds of fuels and the possible advancement of such knowledge in the near future, it is questionable whether the method used in attacking the smoke problem was the best as regards fuel economy. The persistence of smokiness in burning bituminous coals shows that there is room for improvement in methods of burning, or that the best way of utilizing such coals has not been followed.

The volatile matter of bituminous coal would have greater economic value if converted into gas or liquid fuel than if burned under steam boilers. Under present market conditions heat in the form of coal gas brings 8 to 16 times the price of an equivalent amount of heat in the form of coal. Gas is an extremely convenient fuel and can be used to advantage for many purposes such as cooking, lighting and heating buildings, municipal lighting, and in some industrial plants for obtaining a uniformly high temperature and clean products of combustion. The residue from the coking coals should find a ready market for househeating and for steaming purposes. As both the gas and coke burn without smoke, their separate use would tend to make cities cleaner. The manufacture of gas from coal has been a commercial undertaking for many years and is still rapidly developing, the liberal margin between the price of heat in the form of gas and the price of heat in the form of soft coal making the conversion profitable.

The conversion of the volatile matter of bituminous coal into liquid fuel seems to be even more promising than its conversion into gas. By the application of proper processes it seems possible to reduce a large part of the volatile matter to liquid, of which an appreciable percentage can be obtained in the form of light oils suitable for motor fuel. Benzol has been obtained at by-product plants for many years without any special effort to produce it. There is no doubt that with well-developed methods the yield of benzol and similar oils could be greatly increased.

The demand for these oils is already great and will keep on increasing. The value of heat in the form of motor fuel is 20 to 30 times as great as that of heat in the form of coal. As the supply of bituminous coal is enormous, the uses of the oil are practically unlimited, and the margin of profit in the conversion is large, it would seem that the development of highly productive methods would be rapid. By itself the coke residue from such plants would have considerable commercial value, and if its price were made equivalent to that of coal it would doubtless find a wide market for househeating and steaming purposes.

Thus the use of coke and gas would gradually take the place of the use of bituminous coal as fuel and the smoke problem would largely disappear. By using coke under steam boilers they could be kept free from soot and the rate of heat transmission greatly increased. There are probably few instances where coke could not be substituted for coal.

The possibility of converting an appreciable part of the volatile matter of bituminous coal into motor fuel is indicated by Table 4 (p. 78), which gives some of the chemical characteristics of the three coals that were tested in the experimental furnace. The part of coal that can be possibly converted into liquid fuel is the volatile carbon plus the available hydrogen. These two constituents form, on a moisture*and ash free basis, about 13 per cent of the Pocahontas coal, 26 per cent of the Pittsburgh coal, and 34 per cent of the Illinois coal. The ratios of the volatile carbon to the available hydrogen for the three coals are 2.15, 4.36, and 6.6, respectively. The ratio of carbon to hydrogen in benzol (C_6H_6) is 12, the ratio of carbon to hydrogen in gasoline is about 5.3, computed from the average molecular formula of gasoline, C_8H_{18} . Evidently there is more than enough hydrogen for the volatile carbon to form benzol or gasoline. The necessary elements are there, the energy is there; the problem to be solved is to find a way to make the elements form the desired combination.

THE ADVANTAGES OF LIQUID FUEL.

The higher commercial value of liquid fuel is due to its being available for more purposes. Oil seems to have all the advantages of gas and solid fuel and none of their disadvantages. Gas, on account of its simple molecular structure, can be burned readily and without smoke in any commercial apparatus from a boiler furnace to a gas engine; also, the feed of gas can be made automatic for any apparatus and can be easily controlled. However, gas has the great disadvantage that it is not concentrated enough for convenient storage. On the other hand, coal contains large amounts of heat in highly concentrated form and can be easily stored. Its complex molecular structure and the many solid impurities tend to limit its use. In its

marketed form, coal lacks sufficient adaptability to delicate adjustment or automatic feed control.

Liquid fuel has a simple molecular structure, and the ease with which the light oils are changed to vapor make these oils readily adaptable to many purposes for which gas is used. Oil is a highly concentrated fuel and can be easily stored, transported, and handled.

CONCLUSION.

By such possible changes in the use of bituminous coal as are outlined in the preceding paragraphs, the problem of combustion will be much simplified.

Bituminous coal will probably continue to be used under steam boilers but to a lesser extent. In the future its principal use will be in the by-product plants because of the higher commercial value of the products that can be made from it. The higher the percentage of volatile combustible the higher will be the commercial value of the coal. The time may come when our views of the relative values of different coals will change and we shall consider anthracite as of minor importance as compared with the high-volatile bituminous coals.

Vague reports from Europe indicate that after the war the world will be informed of some extraordinary developments in the utilization of bituminous coal in certain countries, and that these developments will become of pressing importance to manufacturers in the United States.

PUBLICATIONS ON THE UTILIZATION OF COAL AND LIGNITE.

A limited supply of the following publications of the Bureau of Mines has been printed and is available for free distribution until the edition is exhausted. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines.

The Bureau of Mines issues a list, showing all its publications available for free distribution, as well as those obtainable only from the Superintendent of Documents, Government Printing Office, on payment of the price of printing. Interested persons should apply to the Director, Bureau of Mines, for a copy of the latest list.

PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger. 1910. 42 pp., 1 pl., 7 figs.

BULLETIN 4. Features of producer-gas power-plant development in Europe, by R. H. Fernald. 1910. 27 pp., 4 pls., 7 figs.

BULLETIN 5. Washing and coking tests of coal at the fuel-testing plant, Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, G. R. Delamater, J. W. Groves, and K. M. Way. 1910. 62 pp., 1 fig.

BULLETIN 6. Coals available for the manufacture of illuminating gas, by A. H. White and Perry Barker, compiled and revised by H. M. Wilson. 1911. 77 pp., 4 pls., 12 figs.

BULLETIN 24. Binders for coal briquets, by J. E. Mills. 56 pp., 1 fig.

BULLETIN 31. Incidental problems in gas-producer tests, by R. H. Fernald, C. D. Smith, J. K. Clement, and H. A. Grine. 29 pp., 8 figs.

BULLETIN 33. Comparative tests of run-of-mine and briquetted coal on the torpedo boat *Biddle*, by W. T. Ray and Henry Kreisinger. 50 pp., 10 figs.

BULLETIN 36. Alaskan coal problems, by W. L. Fisher. 1911. 32 pp., 1 pl.

BULLETIN 55. The commercial trend of the producer-gas power plant, by R. H. Fernald. 1913. 93 pp., 1 pl., 4 figs.

BULLETIN 58. Fuel-briquetting investigations, July, 1904, to July, 1912, by C. A. Wright. 1913. 277 pp., 21 pls., 3 figs.

BULLETIN 76. United States coals available for export trade, by Van. H. Manning. 1914. 15 pp., 1 pl.

BULLETIN 85. Analyses of mine and car samples of coal collected in the fiscal years 1911 to 1913, by A. C. Fieldner, H. I. Smith, A. H. Fay, and Samuel Sanford. 1914. 444 pp., 2 figs.

BULLETIN 89. Economic methods of utilizing Western lignites, by E. J. Babcock. 1915. 74 pp., 5 pls., 5 figs.

BULLETIN 109. Operating details of gas producers, by R. H. Fernald. 1916. 74 pp.

BULLETIN 116. Methods of sampling delivered coal, and specifications for the purchase of coal for the Government, by G. S. Pope. 1916. 64 pp., 5 pls., 2 figs.

BULLETIN 119. Analyses of coals purchased by the Government during the fiscal years 1908-1915, by G. S. Pope. 1916. 118 pp.

BULLETIN 138. Coking of Illinois coals, by F. K. Ovitz. 1917. 68 pp., 11 pls., 1 fig.

TECHNICAL PAPER 9. The status of the gas producer and of the internal-combustion engine in the utilization of fuels, by R. H. Fernald. 1912. 42 pp., 6 figs.

TECHNICAL PAPER 16. Deterioration and spontaneous heating of coal in storage, a preliminary report, by H. C. Porter and F. K. Ovitz. 1912. 14 pp.

TECHNICAL PAPER 34. Experiments with furnaces for a hand-fired return tubular boiler, by S. B. Flagg, G. C. Cook, and F. E. Woodman. 1914. 32 pp., 1 pl., 4 figs.

TECHNICAL PAPER 50. Metallurgical coke, by A. W. Belden. 1913. 48 pp., 1 pl., 23 figs.

TECHNICAL PAPER 55. The production and use of brown coal in the vicinity of Cologne, Germany, by C. A. Davis. 1913. 15 pp.

TECHNICAL PAPER 63. Factors governing the combustion of coal in boiler furnaces, a preliminary report, by J. K. Clement, J. C. W. Frazer, and C. E. Augustine. 1914. 46 pp., 26 figs.

TECHNICAL PAPER 65. A study of the oxidation of coal, by H. C. Porter. 1914. 30 pp., 12 figs.

TECHNICAL PAPER 76. Notes on the sampling and analysis of coal, by A. C. Fieldner. 1914. 59 pp., 6 figs.

TECHNICAL PAPER 80. Hand firing soft coal under power-plant boilers, by Henry Kreisinger. 1915. 83 pp., 32 figs.

TECHNICAL PAPER 97. Saving fuel in heating a house, by L. P. Breckenridge and S. B. Flagg. 1915. 35 pp., 3 figs.

TECHNICAL PAPER 123. Notes on the uses of low-grade fuel in Europe, by R. H. Fernald. 1915. 37 pp., 4 pls., 4 figs.

TECHNICAL PAPER 137. Combustion in the fuel bed of hand-fired furnaces, by Henry Kreisinger, F. K. Ovitz, and C. E. Augustine. 1916. 76 pp., 2 pls., 21 figs.

TECHNICAL PAPER 140. The primary volatile products of the carbonization of coal, by G. B. Taylor and H. C. Porter. 1916. 59 pp., 1 pl., 25 figs.

PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE SUPER-INTENDENT OF DOCUMENTS.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp. 5 cents.

BULLETIN 8. The flow of heat through furnace walls, by W. T. Ray and Henry Kreisinger. 1911. 32 pp., 19 figs. 5 cents.

BULLETIN 9. Recent development of the producer-gas power plant in the United States, by R. H. Fernald. 82 pp., 2 pls. 15 cents.

BULLETIN 11. The purchase of coal by the Government under specifications, with analyses of coal delivered for the fiscal year 1908-9, by G. S. Pope. 80 pp. 10 cents.

BULLETIN 13. Résumé of producer-gas investigations, October 1, 1904, to June 30, 1910, by R. H. Fernald and C. D. Smith. 1911. 393 pp., 12 pls., 250 figs. 65 cents.

BULLETIN 14. Briquetting tests of lignite at Pittsburgh, Pa., 1908-9, with a chapter on sulphite-pitch binder, by C. L. Wright. 1911. 64 pp., 11 pls., 4 figs. 15 cents.

BULLETIN 18. The transmission of heat into steam boilers, by Henry Kreisinger and W. T. Ray. 1912. 180 pp., 78 figs. 20 cents.

BULLETIN 21. The significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 64 pp., 26 figs. 10 cents.

BULLETIN 22. Analyses of coals in the United States, with descriptions of mine and field samples collected between July 1, 1904, and June 30, 1910, by N. W. Lord, with chapters by J. A. Holmes, F. M. Stanton, A. C. Fieldner, and Samuel Sanford. 1912. Part I, Analyses, pp. 1-321; Part II, Descriptions of samples, pp. 321-1129. 85 cents.

BULLETIN 23. Steaming tests of coals and related investigations, September 1, 1904, to December 31, 1908, by L. P. Breckenridge, Henry Kreisinger, and W. T. Ray. 1912. 380 pp., 2 pls., 94 figs. 50 cents.

BULLETIN 27. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 44 pp., 3 pls., 2 figs. 10 cents.

BULLETIN 30. Briquetting tests at the United States fuel-testing plant, Norfolk, Va., 1907-8, by C. L. Wright. 41 pp., 9 pls. 15 cents.

BULLETIN 34. Tests of run-of-mine and briquetted coal in a locomotive boiler, by W. T. Ray and Henry Kreisinger. 33 pp., 9 figs. 5 cents.

INDEX.

A.	Page.	Page.	
Adams, L. H., work of.....	2	Carbon dioxide, relation of, to combustible	
Air, admission of, to fuel bed.....	7	gases.....	105, 106
regulation of.....	14	to excess air.....	8, 96, 105
in combustion tests, weight of.....	30-53	curves showing.....	95, 106
determination of.....	28	variations in, causes of.....	25
mixing of, with combustible gases.....	5	Carbon monoxide in furnace gases, deter-	
effect of.....	130	mination of.....	21
inadequate, effect of.....	57	proportion of.....	9, 30-53, 98, 99, 100, 106
methods for.....	131, 132	curves showing.....	54
need of.....	129, 130	rate of burning.....	117
rate of feeding.....	7	relation of, to gaseous combustible,	
Air supply, control of.....	14	curves showing.....	107
Air excess.....	8	to heat losses.....	9, 108, 109
heat losses from.....	90, 96	curves showing.....	108
curves showing.....	91-95	to rate of combustion.....	127, 128
in combustion tests.....	30-53	weight of.....	112, 113
in gas samples, proportion of.....	102, 103	Clement, J. K., work of.....	2
method of determining.....	28, 29	Coal, burning of, factors governing..	83, 118, 119, 122
need of.....	134	products of.....	132
proper amount of, determination of..	90	composition of, relation of, to combustion	
relation of, to carbon dioxide in		space.....	7, 8
furnace gases.....	8, 105	for tests, amount of.....	30-53
curves showing.....	106	methods of sampling.....	24, 25
to combustion space.....	90	rate of firing, relation of, to completeness	
curves showing.....	56-60, 74, 75	of combustion.....	7
to completeness of combustion.....	56, 68, 88	utilization of, efficient, factors governing..	1
curves showing.....	63-67, 69-74	<i>See also</i> Anthracite; Bituminous coal;	
to proportion of soot and tar...	113, 115	Illinois coal; Pittsburgh coal;	
curves showing.....	114	Pocahontas coal.	
to rate of combustion.....	126	Coal gas, as fuel, advantages of.....	135
to undeveloped heat of gaseous		Coke, burning of, combustion space required	
combustible.....	68	for.....	87
Anthracite, burning of, combustion space re-		utilization of.....	135, 136
quired for.....	87	Combustible, gaseous, composition of....	9, 106, 107
Ash pit, gas pressure in, during tests.....	30-53	in furnace gases, proportion of.....	35-53,
Augustine, C. E., work of.....	2	55, 61, 98, 99, 100, 105, 106	
B.		curves showing.....	54
Bituminous coal, difficulties in burning.....	134	heat value of, formula for determining..	61, 62
future use of.....	137	mixture of air with.....	5, 57, 130
liquid fuel from.....	135, 136	methods for.....	131, 132
Bonny, V. B., work of.....	2	relation of, to combustion space,	
Breckenridge, L. P., cited.....	5	curves showing.....	56-60
on mixing of air and combustible gases..	131	to excess air.....	90
Bureau of Mines, investigations of.....	1	undeveloped heat of, curves showing..	63-67
C.		factors affecting, curves showing..	74, 75
Carbon in coal, relation of, to oxygen content.	84	formula for determination of.....	61, 62
curves showing.....	85	relation of, to excess air.....	68
volatile, in combustible, determination		curves showing.....	69-72, 73, 74
of.....	81	rate of burning, factors governing...	10, 117, 128
relation of, to combustion space,		<i>See also</i> Carbon monoxide; Hydrocar-	
curves showing.....	80, 82	bons, unsaturated; Hydrogen;	
Carbon dioxide, from combustion of coal...	132, 133	Methane.	
in furnace gases, determination of.....	21	Combustion, effect of excess air on, curves	
proportion of.....	30-53, 98, 99, 100	showing.....	73, 74
curves showing.....	26, 27, 54	factors determining.....	4, 7, 61,
		68, 77, 78, 86, 87, 125, 126, 133, 134	
		relation of combustion space to, curves	
		showing.....	63, 64-67, 74, 75
		relation of excess air to, curves showing..	69-72

	Page.		Page.
Combustion, investigations of, apparatus		Furnace, hand-fired, combustion in, curves	
for.....	1	showing.....	3
scope of.....	3	distillation of volatile matter in....	119, 120
over fuel bed, character of.....	125	feeding of coal and air in, figure showing.....	120
processes of.....	2, 6, 7, 55		G.
curves showing.....	3, 54	Gas, as fuel, disadvantage of.....	136
rate of, control of.....	14	Gas producers, burning of gas in.....	122
determination of.....	127, 128	Gas samplers, construction of.....	16, 17
factors governing.....	4, 127, 128	distribution of, figures showing.....	15, 16, 17, 18
relation of combustion space to, curves		water-cooled, figure showing.....	18
showing.....	56-60	water in, absorption of heat by.....	9, 109, 110
relation of excess air to.....	96	Gases in furnace, composition of.....	4, 21
curves showing.....	94, 95	method of obtaining.....	104
relation of soot and tar to.....	113, 115	variations in.....	8, 56
curves showing.....	114	curves showing.....	54
rate of, variation in.....	61	proportion of excess air in.....	102, 103
stages in.....	2	pressure of, control of.....	14
Combustion space, combustion in.....	4, 10	during combustion tests.....	30-53
gas pressure in.....	30-53	mixture of air with, need of.....	129, 133
large, advantages of.....	105	measurement of.....	23
length of, factors governing.....	55	rapid cooling of, objections to.....	105
curves showing.....	56-60, 63-67	sampling of.....	14, 15, 16, 100, 101
size of, determination of.....	76, 88, 89	apparatus for.....	17, 18
factors affecting.....	7, 68, 78,	figure showing.....	19
79, 83, 87, 90, 96, 133, 134		difficulties in.....	60, 61, 101
curves showing.....	74, 80, 82, 91-95	stratification of.....	8, 60, 97, 101, 102, 103
variations in, results of, curves showing.....	95	<i>See also</i> Combustible, gaseous; Natural gas; Producer gas.	
stratification of gases in.....	97	Georgetown, Ill., coal from, tests of.....	23
temperature in.....	132, 133	Greensburg, Pa., coal from, tests of.....	23
measurement of.....	22	Gregg, E. T., work of.....	2
curves showing.....	22		H.
volume of, factors governing.....	55, 77, 78	Hall, A. E., work of.....	2
curves showing.....	56-60, 63-67	Heat, effect of, on stability of hydrocarbons..	123
		Heat losses in combustion chamber, factors	
E.		causing.....	9, 108-111
Egy, W. L., work of.....	2	curves showing.....	91-95, 108
		Hoffman, E. J., work of.....	2
F.		Hoskins thermocouple, furnace-gas measurements with, curves showing.....	22
Fieldner, A. C., work of.....	2	Hydrocarbon compounds, formulas for.....	119
Firing, rate of, relation of, to completeness of combustion.....	68	Hydrocarbons, burning of.....	118-120, 122, 125
curves showing.....	63-67, 69-72	decomposition of, character of.....	123, 124
effect of relation of, to size of combustion space.....	61	products of.....	123, 124
curves showing.....	74, 75	in furnace gases, determination of.....	21
Frazer, J. C. W., work of.....	2	proportion of.....	10, 43, 50-53, 98, 99, 100
Fuel, liquid, advantages of.....	136, 137	weight of.....	112, 113
demand for.....	136	<i>See also</i> Volatile matter.	
from volatile matter.....	135, 136	Hydrogen in furnace gases, determination of.....	21, 81
uses of.....	136	proportion of.....	9, 35-53, 98, 99, 100
<i>See also</i> Coal; Coke; Natural gas.		rate of burning of.....	117
Fuel bed, admission of air to.....	7	relation of, to gaseous combustible, curves showing.....	107
composition of gases from.....	4, 6, 7, 98, 99, 100	weight of.....	112, 113
function of.....	3, 4		I.
gas pressure over.....	30-53	Illinois coal, analyses of.....	24
heat radiation from, figure showing.....	111	burning of, combustion space required	
zones in.....	2	for.....	76, 77, 79
figure showing.....	3	curves showing.....	80
Furnace, experimental, details of.....	10, 12	factors governing.....	88
purpose of.....	4, 5		
sections through, figure showing.....	11		
view of.....	10		

	Page.		Page.
Illinois coal, burning of, gaseous combustible from, curves showing.....	107	Pittsburgh coal, burning of, gaseous combustible from, curves showing.....	107
heat losses in.....	96, 97	heat losses in, curves showing.....	92, 95
curves showing.....	93, 94, 95	rate of.....	6
rate of.....	6	chemical characteristics of.....	78
chemical characteristics of.....	78	curves showing.....	85
curves showing.....	85	for tests, character of.....	23
relation of, to combustion space, curves showing.....	82	sizes of.....	24
for tests, character of.....	23	tests with, number of.....	25
sizes of.....	24	results of.....	37-45
tests with, number of.....	25	curves showing.....	59, 66, 71, 73, 75
results of.....	46, 53	volatile matter of.....	81
curves showing.....	60, 67, 72, 74	Pittsburgh screenings, burning of, gases from, analyses of.....	98, 99, 100
volatile matter of.....	81	curves showing.....	107
K.		soot and tar from, curves showing.....	114
Kreisinger, Henry, work of.....	2	for tests, character of.....	24
L.		tests of, collection of samples in.....	15, 16
Löwenstein, —, cited.....	132	purpose of.....	76, 77
Lunge, G., cited.....	124	results of.....	50-53
M.		curves showing.....	54, 57, 63, 64, 69, 75
Mellor, J. W., cited.....	86	Pocahontas coal, analyses of.....	24
Methane, burning of.....	116	burning of, combustion space required for.....	76
in furnace gases, determination of.....	21		77, 79
proportion of.....	9, 35-48, 50-53, 98, 99, 100	curves showing.....	80, 82
relation of, to gaseous combustible, curves showing.....	107	factors governing.....	88
weight of.....	112, 113	gaseous combustible from, curves showing.....	107
relative stability of.....	123	heat losses in.....	96, 97
Moisture in coal, effect of, on combustion.....	86, 87	curves showing.....	91, 95
curve showing.....	86	rate of.....	6
Murphy stoker, fuel bed of, composition of gases from.....	6	chemical characteristics of.....	78
sections through, figure showing.....	13	curves showing.....	85
N.		for tests, character of.....	23
Natural gas, method of burning.....	121, 122	sizes of.....	24
Nernst, —, cited.....	132	tests with, number of.....	25
New River, W. Va., coal, burning of, combustion space required for.....	89	results of.....	30-37
composition of.....	89	curves showing.....	58, 65, 70, 74
Nitrogen in furnace gases, proportion of.....	35-53, 98, 99, 100	volatile matter of.....	81
O.		Producer gas for furnaces, method of burning.....	121, 122
Ovitz, F. K., work of.....	2	R.	
Oxygen in coal, relation of, to burning quality.....	83, 84	Ralston, O. C., cited.....	84
to carbon content.....	84	Ray, W. T., work of.....	2
curves showing.....	85	S.	
to size of combustion space.....	8	Satler, L. L., work of.....	2
curves showing.....	82	Smith, A. L., work of.....	2
in furnace gases, determination of.....	21	Smoke from bituminous coal, elimination of.....	135
proportion of.....	30-53, 98, 99, 100	See also Soot.	
curves showing.....	54	Soot in furnace gases, burning of, factors governing.....	116-118, 123-130
relation of, to rate of combustion.....	127, 128	slow, causes of.....	117
P.		composition of.....	124
Pittsburgh coal, analyses of.....	24	determination of.....	21, 22
burning of, combustion space required for.....	76, 77, 79	formation of.....	9, 116
curves showing.....	80, 82	proportion of.....	98, 99, 100, 112, 113
factors governing.....	88	weight of.....	50-53, 112, 113
		curves showing.....	114
		samples of, collection of.....	20
		Stein, J. P., work of.....	2
		Stokers, mechanical, burning of soft coal in.....	118, 119
		distillation of volatile matter in.....	121
		feeding of coal and air in, figure showing.....	120

T.	Page.	U.	Page.
Tar in furnace gases, combustion of, factors		Uptake, gas pressure in, during combustion	
governing.....	128-130	tests.....	48-53
determination of.....	21, 22	V.	
factors governing.....	125	Virginia, coal from, composition of.....	89
decomposition of, factors in....	115, 124, 125	Vivian, W. Va., coal from, tests of.....	23
rate of.....	115	Volatile matter, burning of, products of.....	9
proportion of.....	98-100, 112, 113	distillation at low temperatures, advan-	
weight of.....	50-53, 112, 113	tages of.....	118
curves showing.....	114	in fuel bed, character of.....	9
samples of, collection of.....	20	production of liquid fuel from.....	135, 136
Tar samplers, distribution of, figures showing.	15, 16	quality of, determination of.....	81
position of, figure showing.....	17	relation of, to combustion space....	78, 79, 81-83
Temperatures in combustion space..	30-53, 132, 133	curves showing.....	80, 82
factors affecting.....	109-111	to excess air supply.....	90
measurement of.....	22	<i>See also</i> Gases named.	
curves showing.....	22	W.	
reduction of, factors governing.....	9	Wanner pyrometer, furnace-gas measure-	
variations in, causes of.....	25	ments with, curves showing.....	22
curves showing.....	26, 27	Wartenberg, —, cited.....	132
Time, as factor in combustion of coal.....	133, 134	Water, from combustion of coal.....	132
Tuyères, admission of air through.....	14		



K

